Beyond 2000

1999
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2001

science education
for the future

a report with
ten recommendations

Beyond 2000: Science education for the future
The report of a seminar series funded by the Nuffield Foundation

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TRIBUTE
The original proposal and initiative for this report came from the late Professor Rosalind Driver and Dr Jonathan Osborne of King's College London. Rosalind Driver had a passion for science and science education, and an abiding concern for improving the nature and quality of the science education that we offer our young people. It is to be hoped that this report is a fitting contribution to that vision, energy and commitment which was the hallmark of her work.

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1 BACKGROUND AND CONTEXT

THIS REPORT IS THE PRODUCT of a desire to provide a new vision of an education in science for our young people. It is driven by a sense of a growing disparity between the science education provided in our schools and the needs and interests of the young people who will be our future citizens. Education, at the end of the 20th century, no longer prepares individuals for secure, lifelong employment in local industry or services. Rather, the rapid pace of technological change and the globalisation of the marketplace have resulted in a need for individuals who have a broad general education, good communication skills, adaptability and a commitment to lifelong learning. Our view is that the form of science education we currently offer to young people is outmoded, and fundamentally is still a preparatory education for our future scientists. An advanced technological society such as ours will always require a supply of well-qualified research scientists, but this requirement will be met, as at present, by educating and training only a small minority of the population. On the other hand, the ever-growing importance of scientific issues in our daily lives demands a populace who have sufficient knowledge and understanding to follow science and scientific debates with interest, and to engage with the issues science and technology poses – both for them individually, and for our society as a whole. Without a fundamental review and reconsideration of the aims and content of the science curriculum, what we offer our young people is in danger of becoming increasingly irrelevant both to their needs and those of society.

The familiar justifications for science education have also worn thin when confronted by the daily realities of classroom life. Amongst teachers, science educators, curriculum developers, and others engaged or interested in science education at school level, there is now a growing concern about the effectiveness of the existing science curriculum, and its appropriateness as part of the core curriculum. It is this concern which led to a proposal for a series of seminars to consider these issues, which were funded by the Nuffield Foundation.

This report presents the main outcomes of the seminar programme. The aim of the seminars was to consider and review the form of science education required to prepare young people for life in our society in the next century. In addressing our task, the series of seminars considered four principal questions, and these are given on the left. To consider these questions four closed seminars (see Appendix 1 for list of attendees) and two Open Meetings were held between January 1997 and April 1998. The Open Meetings were held in Birmingham (July 1997) and Leeds (April 1998) and attended by approximately 180 people in total.

The recommendations and arguments of this report are essentially, therefore, the ideas emerging from the discussions of twenty people over four weekends and two Open Meetings. Whilst we believe that they offer a new vision and rationale for science education, inevitably we recognise, and hope that others will do so likewise, that they cannot address all the details or resolve all the issues that need to be considered. What the report does offer is a broad framework – a platform from which we hope a new and more relevant contemporary curriculum may emerge.

The ever-growing importance of scientific issues in our daily lives demands a populace who have sufficient knowledge and understanding to follow science and scientific debates.

2 SCIENCE EDUCATION: what we have achieved

EDUCATION IN ENGLAND AND WALES HAS SEEN considerable change in the past forty years. In the 1960s, the tripartite system of grammar, technical and secondary modern schools meant that the majority of pupils were offered a science education of a general or vocational nature. In contrast, the grammar school minority pursued more academic GCE courses which provided a more formal introduction to science and a preparation for further study at A-level. In both cases, biology classes were dominated by girls and physical sciences by boys. During this period, major curriculum innovation was undertaken by the Nuffield Foundation which funded an extensive series of curriculum reforms in the style, if not the content, of courses in all the three main sciences at both O- and A-level. These gave greater emphasis to the role and use of experimental work and have had a significant influence on the practice of science teaching which still persists.

The 'comprehensivisation' of the school structure in the mid 1960s drew attention more forcibly to the needs of the majority. In response, several science courses were developed which sought to provide an appropriate science education for the less academic pupil, notably *Nuffield Secondary Science* in the late 1960s and *Science at Work* in the 1970s. Other courses developed during the 1980s sought to place greater emphasis on the 'processes of science', arguing that the knowledge base was ever-changing and therefore of less value and importance; examples are *Warwick Process Science* and *Science in Process*.

During the 1980s, a consensus was building within science education, articulated forcefully by Her Majesty's Inspectorate in their policy statement *Science 5–16*, that all young people should have a 'broad and balanced' science education between these ages, occupying (for most pupils) 20% of curriculum time from age 14 to 16. This was seen as necessary to ensure a broad, general curriculum for all and to eliminate the strong, gender-related effects in subject choice. Consequently, the introduction in 1986 of the GCSE as a single examination system for all pupils resulted in a variety of science courses that included all three main sciences, that were intended to be suitable for all young people, and also led to a double award GCSE.

Within primary schools, major initiatives to improve science education such as *Science 5–13* in the 1970s had led to a greater awareness of the potential value of science education for children of primary age. However, provision was patchy and the quality variable with too many schools offering an education that failed to transcend the limitations of nature studies. Again, Her Majesty's Inspectorate were influential, arguing in their 1978 survey *Science in Primary Schools* that the progress of science teaching in primary schools had been disappointing. These views contributed to an emergent consensus, set out in the 1985 Policy Statement *Science 5–16*, that science should be a key component of every child's primary education, and that this should include topics from both the physical and biological sciences, taught with an emphasis on practical investigation and inquiry.

Consequently, the National Curriculum, introduced in 1989, made science a

Science is now a universal feature of the curriculum for all pupils from age 5 to 16, and 80% of pupils undertake a double science GCSE at age 16 in a programme which covers all the major sciences.

'core' subject of the curriculum from age 5 to 16. This led to a rapid consolidation of changes of the sort which had been happening gradually in the late 1980s, leading quickly to the situation we have at present: science is now a universal feature of the curriculum for all pupils from age 5 to 16, and 80% of pupils undertake a double science GCSE at age 16 in a programme which covers all the major sciences.

The current significance of science is reflected in the fact that it now occupies the curriculum high table with literacy and numeracy as the essential core of the primary curriculum. In addition, science is also a core subject of the 11–16 curriculum, along with English and mathematics. Moreover, there has been a general acceptance that learning science involves more than simply knowing some facts and ideas about the natural world, and that a significant component of science curriculum time should be devoted to providing opportunities for personal inquiry. Both internal and external indicators point to the success of these changes. Recent OFSTED inspections of primary science have, for example, judged over 80% of lessons to be satisfactory or better. And the results of the Third International Mathematics and Science Survey (TIMSS) have shown improvements, over the past decade, in the performance of English pupils in science, at all ages, relative to their counterparts in other countries, with particularly notable performance in the sub-area of practical science.

The current significance of science is reflected in the fact that it now occupies the curriculum high table with literacy and numeracy as the essential core of the primary curriculum.

3 SCIENCE EDUCATION: the remaining problems

THE CHANGING CURRICULAR POSITION OF SCIENCE has not been accompanied by corresponding change in the *content* of the science curriculum, in particular at secondary level. This has remained fundamentally unaltered and is, essentially, a diluted form of the 1960s GCE curriculum. Whilst there have been some changes in the forms of assessment used, too much of the summative assessment of students is still based on factual recall which bears little relationship to the sorts of situations beyond the classroom, where students may need to apply their scientific knowledge and skill, and where an ability to sift, sort and analyse information is paramount. The predominant aim of science courses of the 1960s was to provide a basis of knowledge for future specialism in science, in a period of confidence in the social benefits of science, and when the 'white heat of technological revolution' was seen as requiring ever-growing numbers of scientists to sustain and develop our industrial productivity. In contrast, contemporary analyses of the labour market would suggest that our future society will need a larger number of individuals with a broader understanding of science both for their work and to enable them to participate as citizens in a democratic society.

Since the 1960s, the image of science has been tarnished by a succession of scientific and technological developments with unforeseen environmental and societal consequences, such as DDT, Chernobyl, Thalidomide, CFCs and the depletion of the ozone layer. In addition, scientific developments have led to public unease about their implications, such as genetic manipulation and cloning. To sustain a healthy and vibrant democracy, such issues do not require an acquiescent (nor a hostile and suspicious) public, but one with a broad understanding of major scientific ideas who, whilst appreciating the value of science and its contribution to our culture, can engage critically with issues and arguments which involve scientific knowledge. For individuals need to be able to understand the methods by which science derives the evidence for the claims made by scientists; to appreciate the strengths and limits of scientific evidence; to be able to make a sensible assessment of risk; and to recognise the ethical and moral implications of the choices that science offers for action.

However the current curriculum retains its past, mid-twentieth-century emphasis, presenting science as a body of knowledge which is value-free, objective and detached – a succession of 'facts' to be learnt, with insufficient indication of any overarching coherence and a lack of contextual relevance to the future needs of young people. The result is a growing tension between school science and contemporary science as portrayed in the media, between the needs of future specialists and the needs of young people in the workplace and as informed citizens.

These problems are structural and underlying ones. However, they show themselves in a number of more readily visible ways.

- Too many young people complete their compulsory science education with apparent success, and yet still lack any familiarity with the scientific ideas which

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they are likely to meet outside school. Even for those who 'succeed' with the current curriculum, the kind of 'understanding' they achieve does not equip them to deal effectively and confidently with scientific information in everyday contexts.

- School science, particularly at secondary level, fails to sustain and develop the sense of wonder and curiosity of many young people about the natural world. This interest and inquisitiveness which characterises many primary school children's response to science diminishes at secondary level to a degree which cannot wholly be accounted for by the onset of adolescence. The apparent lack of relevance of the school science curriculum to teenagers' curiosity and interests contributes to too few young people choosing to pursue solely courses in science and mathematics post-16, preferring instead to follow either courses in the humanities or a mixed combination drawn from a range of disciplines.

From our experience of the current science curriculum, we would suggest the following reasons for these problems of outcome and pupil response.

- The science curriculum can appear as a 'catalogue' of discrete ideas, lacking coherence or relevance. There is an over-emphasis on content which is often taught in isolation from the kinds of contexts which could provide essential relevance and meaning. Insufficient emphasis is given to showing the tremendous intellectual achievement such ideas represent, and how they have transformed our conception of ourselves and the world we inhabit. The existing stress on content limits the study of components such as the nature of science; the role of scientific evidence, probability and risk; and the ways in which scientists justify their knowledge claims – all of which are important aspects necessary to understand the practice of science.

- The science curriculum lacks a well-articulated set of aims or an agreed model of the development of pupils' scientific capability over the 5–16 period and beyond. This makes it hard for primary teachers to see how the foundations they provide will be built upon (and to teach so as to facilitate this); and hard for secondary teachers to build upon the knowledge and skills pupils have acquired at primary school.

- Assessment is based on exercises and tasks that rely heavily on memorisation and recall, and are quite unlike those contexts in which learners might wish to use science knowledge or skills in later life (such as understanding media reports, and understanding the basis of personal decisions about health and diet).

- The National Curriculum separates science and technology. Research, however, suggests that many young people perceive the purpose of the scientific endeavour substantially in terms of its technological products. Such a distinction is therefore unhelpful, as not only are the two inseparably intertwined in the public mind, but the science then appears detached and irrelevant to young people's concerns and interests.

- There is relatively little emphasis, within the science curriculum, on discussion or analysis of any of the scientific issues that permeate contemporary life.

The science curriculum lacks a well-articulated set of aims or an agreed model of the development of pupils' scientific capability over the 5–16 period and beyond.

We would also suggest that the current curriculum and assessment framework has the following results.

- There is a lack of variety of teaching and learning experiences leading to too many dull and uninspiring lessons. Sometimes routine practical work is used where other learning strategies might be more effective. Even investigations, an innovative practice introduced by the National Curriculum itself, are in danger of succumbing to routine teaching as a consequence of perceived assessment requirements.

- There is a lack of choice post-14 and, as a consequence, a science curriculum which fails to take adequate account of the diversity of interests and aptitudes of young people of this age.

Single award science courses have nearly all of these problems more acutely and are insufficiently differentiated from the double science courses, in either their intent or content.

Given these continuing problems and difficulties, the questions we have asked and considered in the seminars are: 'Why does an education in science matter?' and 'Who is science education for?' In the following section, we will discuss our answers to these questions, and go on to consider the structure and content of the science curriculum to which these answers point.

Questions we have asked and considered in the seminars are: 'Why does an education in science matter?' and 'Who is science education for?

4 THE ROLE OF SCIENCE IN THE CURRICULUM

4.1 WHY DOES AN EDUCATION IN SCIENCE MATTER?

The great achievement of the sciences, over the past three or four hundred years, has been to tell us important and interesting new things about ourselves and the world in which we live. They by no means tell us everything, or even the most important things we want to know about the world. But what they do, uniquely, is to offer a knowledge that can be relied on for action. This reliable knowledge is much more than a compendium of things that happen to have been observed; it presents the world in novel and surprising guises, saying that things are in reality often not as they seem to be. Science tells us, for example, that diseases are carried by micro-organisms invisible to the naked eye; that heritable traits are carried by a chemical code; that all species have evolved from simpler organisms; that all substances are made of tiny particles held together by forces which are electrical in nature; that the many varied substances we see around us are made up of different re-arrangements of the same few particles; that we live on a rocky ball with a hot interior which circles the Sun; and that the Universe had its beginning in a huge explosion. Acting on the reliable knowledge which science has produced, scientists have developed a staggering variety of artefacts and products, ranging from electric motors to antibiotics, and from artificial satellites to genetically engineered insulin for treating diabetes, which have transformed our lives and lifestyles as compared with those of past generations.

Science deals with major themes in which most people are already interested, or can readily be interested: life and living things, matter, the Universe, information, the 'made-world'. A primary reason, therefore, for teaching science to young people is to pass on to them some of this knowledge about the material world, simply because it is both interesting and important – and to convey the sense of excitement that scientific knowledge brings. It is not the sort of knowledge which will be learned simply through experience, but needs to be handed on through carefully planned teaching. On a practical level, an understanding of scientific ideas can help people in decision-making (for example, about diet, health, and lifestyle more generally), and in feeling empowered to hold and express a view on issues which enter the arena of public debate and, perhaps, to become actively involved in some of these.

Science has transformed not only our material environment but also the way we think of ourselves, of the Universe we inhabit, and of our place within it. The 'stories' which science tells about the material world and how it behaves have made an enormous contribution to our culture. So too has the scientific approach to inquiry, based on evidence and careful reasoning, with all claims open to critical scrutiny by a community of inquirers, and founded upon an underlying commitment to seek material explanations for events in a material Universe which is assumed to behave regularly and uniformly, in a 'lawful' and non-capricious way. The influence of these ideas about the Universe, and about how to obtain reliable

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knowledge, can be seen in art and literature, in our institutional structures, and in the values we hold important. Not to have some understanding of them is to be, in a very real sense, an 'outsider', excluded from elements of our common culture in much the same way as a person who is unable to read. Another reason, then, for teaching science is to enable young people to become 'scientifically literate' – able to engage with the ideas and views which form such a central part of our common culture.

By considering the ways in which evidence and argument have been employed to establish reliable knowledge about the natural world, and by gaining experience in developing one's own arguments, and in scrutinising those of others about natural phenomena, patterns and regularities in events, and possible explanations for them, young people acquire and develop important skills and understandings. These can then be used in a wide range of contexts and settings in later life, in vocational and social contexts.

Finally, science education also matters because we value the products of science and technology which permeate our daily lives, and the beneficial applications of scientific knowledge in medicine, agriculture, communications, new materials and so on. We need, as a society, to train and educate new generations of scientists and technologists to maintain the technological tools and systems we value and to develop new and better ones to meet new needs and solve new problems. School science is, for some young people, the start of the process which will enable them to become the scientists and technologists of the future.

4.2 WHO IS SCHOOL SCIENCE EDUCATION FOR?

It is our view that the enormous impact of the products of science on our everyday lives, and of scientific ideas on our common culture, justify the place of science as a core subject of the school curriculum, studied by all young people from 5 to 16.

Primary science is important because it provides a framework for developing children's innate curiosity about their natural environment. It fosters habits of careful observation and the use of precise language for descriptive purposes. Furthermore, it provides contexts for practising measurement and the use of number. More fundamentally, however, establishing any understanding of the world requires opportunities to interact with the wide variety of natural phenomena that exist, to investigate their behaviour, and to learn how they are talked about. Such experiences are essential to constructing the basic representations and concepts on which a more sophisticated understanding of science and technology rests – something which the secondary school attempts to build. It begins the lengthy process of developing the ability to produce and understand scientific arguments, using reliable and agreed evidence to support conclusions. It provides a natural opportunity to begin to engage with non-fiction texts and their interpretation. In this way, primary science supports the curriculum priorities of literacy and numeracy, whilst adding an important dimension that would otherwise be lacking; it starts the development of young children's capability in reasoning from evidence, using clearly and precisely defined concepts and ideas.

Nor do we believe that the study of science should become optional beyond the age of 14 for any young people. For the impact of science on our material and intellectual culture is simply too great, and many of the issues which we need to

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explore with young people, and about which we would wish to help them develop an informed view (such as genetics, chemical interactions, and radioactivity), require a level of cognitive development and maturity about social interactions and affairs which few have attained by the age of 14. We therefore believe that the study of science should remain part of every young person's education to the age of 16 if young people are to achieve a basic familiarity with scientific concepts which is essential for engaging with contemporary science.

RECOMMENDATION ONE

The science curriculum from 5 to 16 should be seen primarily as a course to enhance general 'scientific literacy'.

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. Its content and structure must be justified in these terms, and not as a preparation for further, more advanced study.

To say this is not, however, to disregard the needs of those young people who choose to pursue the formal study of science beyond age 16. The curriculum needs to cater for this choice, as it does for other personal and socially valuable choices and interests. Society, as we have noted above, does need a steady flow of people wishing to become science specialists. But this is a route which only a minority of the 5–16 population will follow, and it should not therefore be allowed to influence unduly the form and content of the science curriculum offered to the majority. Our view is that the primary and explicit aim of the 5–16 science curriculum should be to provide a course which can enhance 'scientific literacy', as this is necessary for all young people growing up in our society, whatever their career aspirations or aptitudes.

By our first recommendation we mean that school science education should aim to produce a populace who are comfortable, competent and confident with scientific and technical matters and artefacts. The science curriculum should provide sufficient scientific knowledge and understanding to enable students to read simple newspaper articles about science, and to follow TV programmes on new advances in science with interest. Such an education should enable them to express an opinion on important social and ethical issues with which they will increasingly be confronted. It will also form a viable basis, should the need arise, for retraining in work related to science or technology in their later careers.

4.3 CURRICULUM CHOICE

We believe that insufficient attention has, hitherto, been paid to the tension between the aims of promoting 'scientific literacy' on the one hand, and providing the first stage of a training in science on the other. Science educators have been rather too ready to accept that the same curriculum can serve both purposes. The issue is most acute at Key Stage 4, where the similarities in structure and content between the science National Curriculum and its predecessors, GCSE Science and GCE O-levels in the separate sciences, outweigh the differences – yet O-level was intended

For the majority of young people, the 5 – 16 science curriculum will be an end-in-itself.

for around 25% of the population whereas the National Curriculum is for the entire cohort. Whilst it may have been acceptable for GCE O-level to be designed, essentially, as the first stage of a training in science, leading easily on to more advanced courses, this is clearly an inappropriate model for a curriculum for all young people – the majority of whom will not follow this path.

We believe that it is essential that we now recognise this tension within science education and deal with it in an explicit and productive way. For, if we do not, then the needs of a minority for a suitable preparation for more advanced study will continue to distort the science course which is provided for the majority of young people, to an unacceptable degree.

RECOMMENDATION TWO

At Key Stage 4, the structure of the science curriculum needs to differentiate more explicitly between those elements designed to enhance 'scientific literacy', and those designed as the early stages of a specialist training in science, so that the requirement for the latter does not come to distort the former.

UP TO THE END OF KEY Stage 3, we think it is appropriate to provide a common curriculum, with the necessary differentiation to accommodate the differing interests and aptitudes of learners being managed by the teacher, within a single overall curriculum specification. At Key Stage 4, however, we recognise the need for greater diversity. Here a structure is required which will ensure that all pupils experience a course which can provide the sort of understanding and appreciation of science which every citizen should have – whilst acknowledging that some will wish to proceed to a more advanced study of science beyond age 16. The challenge is to facilitate such choice, without allowing it to influence unduly the overall science provision.

It is our view that the pattern of science curriculum which has become established over the past fifteen years, whereby most pupils aged 14–16 follow a science course for 20% of their curriculum time leading to a double award GCSE in Science, is the best means of achieving these aims. The internal structure of this 20% time allocation needs, however, to be re-thought, to provide greater diversity of science education provision and to facilitate greater flexibility in the construction of schools' and individual pupils' timetables. We would recommend that half of this time (10% of total curriculum time) be taken up by *a statutory course for all pupils*, designed to enhance 'scientific literacy', along the lines outlined in this report. This would then replace the current 'Single Award Science', which is widely seen as unsatisfactory. Alongside this core provision, we would then envisage a wide choice of science options, including modules of a more academic and of a more vocational kind, which could be taken by pupils in a variety of combinations. Different choices within this 'further' science time would facilitate different post-16 options, but we would want to see these modules continuing to be readily available to students throughout the 14–19 period and beyond, to make it easy for young people to pick up additional modules at different stages and so avoid closing off career options prematurely, or irrevocably. Moreover, it is important that all options offer a qualification that is valued by both society and students alike.

Up to the end of Key Stage 3, we think it is appropriate to provide a common curriculum. At Key Stage 4, however, we recognise the need for greater diversity.

5 DESIGNING A NEW SCIENCE CURRICULUM

5.1 SCIENCE CURRICULUM: AIMS

We need now to make clearer what we mean by a course to enhance 'scientific literacy'. The essential first step is to clarify the aims of such a course. One of the weaknesses of the current science curriculum is that its aims are not clearly stated. As a result there is no way of knowing the intended purpose of any specific content of the curriculum, or the criteria on which the selection and organisation of content is based. We recognise that any statement of aims runs the risk of being bland and general (and hence unexceptionable). Nonetheless, we think it is important to try to state clearly and directly the purposes for which we wish to teach science to all our young people, in order to provide criteria for selecting appropriate content and teaching approaches.

RECOMMENDATION THREE

The science curriculum needs to contain a clear statement of its *aims* – making clear *why* we consider it valuable for all our young people to study science, and *what* we would wish them to gain from the experience. These aims need to be clear, and easily understood by teachers, pupils and parents. They also need to be realistic and achievable.

THE AIMS WE WOULD wish for the science curriculum are set out below. In stating the aims of the science curriculum in this way, we are, quite intentionally, emphasising the cultural and democratic justifications for an understanding of science. We believe that these are the main arguments for seeking to improve the understanding of science within the general population. We have given less emphasis to the oft-used argument that science should be taught because scientific knowledge is useful for action. We feel that this rationale has been over-used by teachers and others, and has led to disaffection amongst learners when the utility of the knowledge they are offered in science lessons is less than readily apparent. In fact, scientific knowledge usually has to be re-worked and re-structured before it can be applied to most everyday situations, because these are more complex and 'untidy' than the simplified situations used in the teaching laboratory to introduce the ideas to learners. It is also the case that increasing technological sophistication is reducing, rather than increasing, the need for people to understand the principles on which devices and artefacts are based. We can use computers, motor cars, TVs, video recorders and so on with almost no understanding of how they work – and fewer and fewer repair jobs can be carried out by non-experts. Even the plugs for electrical appliances are now supplied pre-wired and moulded on!

We also believe that young people need an understanding of how scientific inquiry is conducted – to help them appreciate the reasoning which underpins

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scientific knowledge claims, so that they are better able to appreciate both the strengths and the limitations of such claims, in a range of situations and contexts. We would, however, suggest that the argument that an understanding of the methods of scientific inquiry is practically useful in everyday contexts has been over-emphasised. For most purposes a systematic, common-sense approach will suffice.

Aims of the science curriculum

The purpose of science education, as a component of young people's whole educational experience, is to prepare them for a full and satisfying life in the world of the 21st century. More specifically, the science curriculum should:

❖ sustain and develop the curiosity of young people about the natural world around them, and build up their confidence in their ability to inquire into its behaviour. It should seek to foster a sense of wonder, enthusiasm and interest in science so that young people feel confident and competent to engage with scientific and technical matters.

❖ help young people acquire a broad, general understanding of the important ideas and explanatory frameworks of science, and of the procedures of scientific inquiry, which have had a major impact on our material environment and on our culture in general, so that they can:

- appreciate why these ideas are valued;
- appreciate the underlying rationale for decisions (for example about diet, or medical treatment, or energy use) which they may wish, or be advised, to take in everyday contexts, both now and in later life;
- be able to understand, and respond critically to, media reports of issues with a science component;
- feel empowered to hold and express a personal point of view on issues with a science component which enter the arena of public debate, and perhaps to become actively involved in some of these;
- acquire further knowledge when required, either for interest or for vocational purposes.

We have set out our views on the aims of science education for all young people in some detail because we believe it is important to be clear about why we believe science has a right to be considered, alongside literacy and numeracy, as a core element of the curriculum. The value of literacy and numeracy is uncontested, but often there is a lack of clarity about the value of science education. A clear statement of aims will help to communicate the value of science education to people beyond the scientific establishment – to a wider public, many of whom may feel ill-educated in science and reluctant to acknowledge its value. We see the aim of improving scientific literacy, as we have characterised it above, as a vital one if we are to create the social and political climate within which science and its products can be both appropriately valued and appropriately controlled in a democracy.

A clear statement of aims will help to communicate the value of science education to people beyond the scientific establishment.

5.2 PRESENTING THE CURRICULUM

5.2.1 'Explanatory stories'

The heart of the cultural contribution of science is a set of major ideas about the material world and how it behaves, such as the particle model of matter, the germ theory of infectious disease, the gene model of inheritance, the heliocentric model of the Solar System, and so on. It follows that these ideas and themes should be prominent within the science curriculum.

Such ideas fall within the broad themes of life and living things, matter, the Universe, and the made-world. These are all areas where the sciences have something fundamental to say, and together they display a good deal of the variety to be found amongst scientific ideas and scientific thinking. However, in focussing 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.

Our proposal is that science education should make much greater use of one of the world's most powerful and pervasive ways of communicating ideas – the narrative form – by recognising that its central aim is to present a series of 'explanatory stories'. By this we mean that science has an account to offer in response to such questions as 'How do we catch diseases?', 'How old is the Earth and how did it come to be?', 'How come there is such inordinate variety of living things here on Earth?' It is these accounts ('explanatory stories') and their broad features which interest and engage pupils and, therefore, it is these accounts that any science curriculum needs to keep firmly in its sights and as its curriculum aims. By using the word 'stories' we do not, of course, wish to suggest that the explanatory accounts provided by science are 'mere fictions'. Rather we want to emphasise the value of the narrative in communicating ideas and in making ideas coherent, memorable and meaningful. We would argue, therefore, that there is considerable value and advantage in presenting the knowledge content of the curriculum as a set of 'explanatory stories' for the following reasons.

- These stories emphasise that understanding is not of single propositions, or concepts, but of *inter-related sets of ideas* which, taken together, provide a framework for understanding an area of experience.

- They help to ensure that the *central ideas of the curriculum are not obscured*

In focussing on the detail, we have lost sight of the major ideas that science has to tell, and we propose that science education should make much greater use of one of the world's most powerful and pervasive ways of communicating ideas – the narrative form.

by the weight of detail. Pupils and teachers are then able to see more clearly where ideas are leading, and how they are inter-related – and so be able to work together more effectively towards clear targets.

They provide a better portrayal of *the sort of understanding we would wish young people to obtain* from studying the science curriculum than do lists of separate knowledge statements – and hence a better pointer to the kinds of assessment approach which might be suitable.

RECOMMENDATION FOUR

The curriculum needs to be presented clearly and simply, and its content needs to be seen to follow from the statement of aims (above). Scientific knowledge can best be presented in the curriculum as a number of key 'explanatory stories'. In addition, the curriculum should introduce young people to a number of important ideas-about-science.

MOREOVER, BY PRESENTING some of these ideas through historical case-studies, we can show more clearly the contribution that science has made to our culture. An understanding of the same 'explanatory stories' is also necessary for interpreting, and appropriately responding to, media reports of science-related issues and science-related decisions in everyday settings, thus strengthening the case for giving them prominence within the science curriculum.

To illustrate what we mean by an 'explanatory story', we set out two of the important 'stories' of science below in the form of the understanding we would wish pupils to gain by age 16 and in addition, for one of the stories, how the story might be 'constructed' through the relevant key stages. 'Telling the stories' will, of course, often involve the use of illustrative practical work to allow pupils to see the phenomena being discussed, and to help them develop an understanding of the key ideas. It is of course important that young people see these 'stories' not as 'given' knowledge but as the product of sustained inquiry by individuals working in social and historical contexts. They should gain some understanding of where these ideas have come from, and of the warrants we have for trusting them as reliable knowledge. This aspect of the science curriculum is discussed further in section 5.2.4.

Two typical 'explanatory stories' of science

ONE
THE PARTICLE MODEL OF CHEMICAL REACTIONS

Imagine being able to 'peek inside' matter. Then you would 'see' that matter is made of tiny particles of less than a 100 different types. These particles, called atoms, move about, arranging or re-arranging themselves in patterns or sticking together to make new, more complex particles. Alternatively, complex particles can be broken up into their constituent atoms.

Seen at this level, breaking a brick tears particles apart from each other, as links between the particles are broken. Water evaporating is a few particles breaking free of the large collection in the puddle to move freely in the air above. Salt dissolving is charged particles breaking free from the surface of the crystal of salt, dispersing themselves amongst the particles of water. Iron rusting is particles from the air (oxygen, water) bumping into the particles of iron and combining to make a new bigger particle. Polythene is made when particles of ethene, whizzing freely around, join up in long chains when they bump into one another. Big complex particles (enzymes) act on others by being the right shape to help other particles come together and combine.

Some of the particles are made of a single nucleus surrounded by electrons. If you looked around, you would find only 92 stable kinds, differing from each other by the positive charge on the nucleus (from 1 to 92) and their weight. Helium particles, for instance, would be four times as heavy as those of hydrogen. Each particle would be surrounded by an equal number of negative electrons so that any atom is electrically neutral. The electrons are arranged in a characteristic pattern, and the pattern repeats itself so that certain atoms have similar behaviour and fall into natural families. This pattern also decides which kinds of atoms any atom would readily stick to.

When atoms join together in clusters they are called molecules. When atoms combine, the electron arrangement changes giving the new molecule totally different properties. So sodium (a highly reactive metal) can combine with chlorine (a highly reactive and poisonous gas) to make sodium chloride (common salt which we eat). This is how atoms and molecules make the huge number of different materials that there are – the many ‘chemical compounds’. So when atoms break apart and regroup, a ‘chemical change’ has occurred and the new substance is different from its constituent atoms.

At Key Stage 1 and 2, pupils will get a range of experiences of chemical change (though it will not necessarily be labelled as such), both in and out of school. For instance, cooking involves chemical change, as does burning, rusting and the decay of organic matter. Pupils may get to see examples of gas being evolved in a reaction, for instance when a vitamin C tablet is put into water. Through activities on sorting and classifying materials, they will build up a vocabulary for talking about properties, which can then be applied to discussing differences between solids, liquids and gases. Pupils can be helped to appreciate that gases are ‘real substances’ which take up space. Through activities on separating substances they can begin to develop ideas about the small size of the basic particles of substances which can pass through filter paper.

At Key Stage 3, the main ideas of the ‘explanatory story’ of chemical reactions can be developed. Recognising that gases have weight, and noting that mass is conserved in chemical reactions, provide clues to support the ‘explanatory story’ that matter consists of indestructible particles. An understanding of the nature and composition of air also enables combustion to be included in the ‘story’. Ideas of substance and ‘purity’ can be clarified. Pupils might also learn of the role of scientists like Black, Lavoisier, Avogadro, Dalton and others in developing these ideas. They may also be helped to see the implications of the conservation of mass in reactions for waste disposal and the pollution of water and air.

Work at Key Stage 4 builds on this understanding by developing ideas about bonds between atoms within molecules, and between molecules. Pupils should gain knowledge of a wider range of substances and types of chemical reaction, such as acids/alkalis, hydrocarbons and plastics. They may be introduced to chemical equations and to the use of the basic model to calculate amounts of reacting materials or of products. A more detailed 'explanatory story' about the internal structure of atoms provides a framework for understanding the differences and similarities between atoms and the way in which they bond.

TWO THE EARTH AND BEYOND

From our point of view on the Earth, it seems that we are living on a flat stationary surface. However, imagine moving to a point in Space, well away from the Earth. Then we would see that it is roughly a sphere which is moving in two ways. First, the Earth is spinning on an axis through its North and South Poles; this means that different parts of the Earth's surface point towards the Sun at different times, resulting in day and night. Second, it is also moving, roughly in a circle, round the Sun, taking one year to make a complete orbit. The Earth is kept in its orbit by the gravitational force between the two masses of the Sun and the Earth. Because the axis around which the Earth spins is tilted at an angle to the plane of its orbit, the relative lengths of day and night are different for the northern and southern hemispheres and, moreover, change as the Earth moves round its orbit. This is what causes the seasons.

In both our spinning and our orbital motion, we keep on going at a steady speed, unlike things here on Earth, because there is no friction to slow us down. We are not the only planet going round the Sun; there are others. Three of them (Mars, Venus and Mercury) are close to the Sun like us. Then there are two really big ones (Jupiter and Saturn), very different from us and much further away. Finally there are the outer ones which are very much further away and really cold. Several of the planets, including the Earth, have moons which orbit around them.

Of the planets, the only one with life on it (so far as we know) is the Earth. It is possible that there is life on Mars and one of the moons of Jupiter, but we don't know. If we did find life there as well, it would make the possibility of other life elsewhere in the Universe much more likely.

Our planet is really quite unusual. Whilst most of the Universe consists of hydrogen and helium, we live on a tiny rocky planet made out of elements which together make up less than 2% of all the matter in the Universe. Moreover, we are just sufficiently far from the Sun for water to be a liquid on the majority of the surface. This has enabled life to begin. We are also big enough for there to be sufficient gravity to keep our atmosphere, unlike Mercury or the Moon.

Surprisingly, the Sun is a star – a fairly ordinary, middle-aged star half way through its lifetime and a wonderful example of a balanced nuclear fusion reaction. How do we know? Well firstly, this is the only mechanism that could possibly produce so much energy and, secondly, theoretical models based on this idea predict the behaviour of the Sun quite accurately. The Sun looks bigger than all the other stars because it is much nearer. The Sun itself is just one star in a cluster of a hundred thousand million stars which we call a galaxy. You can see the cluster edge on in the night sky as a band of stars called the 'Milky Way'. There are hundreds of millions of galaxies and these are found in clusters as well. Distances to the stars are enormous – the nearest one would take four years to reach travelling at the speed of light, and the furthest known one is 12 billion years away. So our home, the Earth, is really just a tiny speck in an enormous Universe.

5.2.2 Choosing and organising the 'stories'

The breadth and extent of scientific knowledge now ranges over such a wide field from evolutionary biology to modern cosmology that some selection must be made in constructing a curriculum – it is simply not possible to cover the whole breadth of science. Therefore, as choice is inevitable, we should resist the temptation to include too much, and so avoid ending up with a content-dominated curriculum which leaves insufficient time for discussion, reflection and analysis. For instance, we believe that some of these 'explanatory stories' will need to be presented through historical case-studies if we are to show science more clearly as a key element of our culture. This will require time for research, presentation and discussion. We believe that if the science curriculum were to set out to communicate the core ideas of science as 'explanatory stories', concentrating on the essential structure of explanations and a general overview, and not on the details, then this change would permit a significant reduction in 'content', allowing space for other kinds of activity and learning.

The reason why the aims set out in section 5.1 above are of crucial importance is that they provide criteria for making the necessary choice of which 'explanatory stories' to include. From both the cultural and democratic perspectives, there are several quintessential 'explanatory stories' that merit a place on the curriculum.

In the area of life and living things, science tells us:

- about the human body as a set of inter-related organ systems (the circulation of blood, digestion, respiration, and so on); the maintenance of good health, and the causes of poor health (invasion by germs, environmental causes, genetic causes, old age, poor mental functioning);
- about cells as the basic building blocks of all living organisms;
- about the ways in which organisms are adapted to the physical and biological environments in which they find themselves;
- about life processes in green plants, particularly photosynthesis;
- about the mechanisms by which characteristics are handed on from one generation to the next;
- about the gradual evolution of species through natural selection.

This last 'story' introduces important and challenging ideas about the huge time-scales over which change occurs. Moreover, it offers us a radically different view of who we are – the product of random variation and selective survival.

From its investigations of natural phenomena, science also offers us major 'explanatory stories' at the microscopic level about:

- how all matter is made of tiny particles;

We should resist the temptation to include too much, and so avoid ending up with a content-dominated curriculum.

- the model of chemical reactions as re-arrangements of the particles of the reactants to form new substances;
- the idea of different kinds of bonding between particles, explaining the very different behaviours of different types of matter.

In contrast, at the macroscopic level, science tells us 'explanatory stories' which are often strange and unfamiliar about:

- the motion of the Earth on its axis and around the Sun, and how this explains day and night and the seasons;
- the structure of the Solar System;
- the formation and evolution of the Earth;
- the structure and evolution of the Universe (a story about galaxies moving away from each other at high speed; about the birth, life and death of stars; about the formation of heavy elements in these stellar processes; and about the origin of the Universe in a Big Bang);
- forces that act over very large distances with no tangible connection involved;
- the causes of motion and its control;
- the causes and direction of change;
- radiation, light and their interaction with matter.

These ideas, like those concerning evolution, again involve coming to terms with the huge time-scale of events and processes, and also the huge scale of size and distance.

5.2.3 Science and technology

In the popular mind, science-and-technology is often seen as a single entity. It would therefore be artificial to separate the two and attempt to teach only 'pure' science. Furthermore, most people would expect a science education to provide some understanding of the principles underlying the technical developments which have been influential on our lifestyle, and develop some appreciation of their impact on the way we live. Technology is not simply applied science – it is the cultural response of people to problems and opportunities they have perceived which has shaped the ways we live and work. Hence some understanding of technology is basic to scientific literacy and our ability to express an opinion on matters that affect us deeply.

The Design and Technology (D&T) Curriculum provides valuable experiences of designing and making simple artefacts, and of using some of the more complex ones (such as motors, computer control and CAD). In science education, there are

In the popular mind, science-and-technology is often seen as a single entity. It would therefore be artificial to separate the two and attempt to teach only 'pure' science.

two essential components to add which are necessary to address the aims set out in section 5.1. Firstly, young people's natural curiosity about technology is a hook on which we can build an understanding of science, as the *Salters'* courses have shown. Using the 'explanatory stories' of science we can show how some of the artefacts which so permeate our lives (such as the telephone, the radio, the television, the fridge, the microwave, the internal combustion engine, and the computer) function. Secondly, we can go beyond the limitations of the D&T workshop to explore larger technologies and their implications for society, such as the generation and use of electricity, the functioning of modern agriculture and the production of food, the construction of contemporary buildings and structures, the technology of modern transport systems, and the workings of the health and pharmaceuticals industries.

CURRENTLY, THIS ASPECT of the curriculum is under-emphasised. Yet not only is it significant to young people, but also the explanations that science can offer will make them more aware of the impact of the products of science and technology on their lives, and more knowledgeable about how they work. We do acknowledge, however, that there is work to do to explore the implications of teaching part of the science curriculum with the aim of 'technical know-how' rather than abstract formal knowledge, and to propose ways in which it might be done.

RECOMMENDATION FIVE

Work should be undertaken to explore how aspects of technology and the applications of science currently omitted could be incorporated within a science curriculum designed to enhance 'scientific literacy'.

Finally, we feel it important to acknowledge that the twentieth century has seen the rapid development of a cluster of sciences and technologies concerned with the transmission, storage, processing and replication of information. They provide the framework for understanding channels of communication from telephone lines, to satellite communication, and to fibre-optic cables. They are the basis for understanding the nature and functioning of computers. They underlie our understanding of how biological systems reproduce themselves and how their form and behaviour are controlled. They offer some future hope of understanding how brains work. Yet they are almost wholly absent from the curriculum.

Taken together, all these points would suggest that the importance of technology to the science curriculum is such that its curricular implications should be explored as a matter of some urgency.

5.2.4 Ideas-about-science

In order to understand the major 'explanatory stories' of science, and to use this understanding in interpreting everyday decisions and media reports, young people also require an understanding of the scientific approach to inquiry. Only then can they appreciate both the power, and the limitations, of different kinds of scientific knowledge claims. They also need to be aware of the difficulties of obtaining reliable and valid data. Science issues are often about the presence or absence of links and correlations between factors and variables, often of a statistical and probabilistic

The importance of technology to the science curriculum is such that its curricular implications should be explored as a matter of some urgency.

kind, rather than directly causal – so young people need an understanding of these ideas, and practice in reasoning about such situations. Often the plausibility of a claimed link depends on seeing a mechanism which might be responsible – and here again an understanding of the major 'explanatory stories' of science is needed. Finally, young people need some understanding of the social processes internal to science itself, which are used to test and scrutinise knowledge claims before they can become widely accepted – in order to appreciate their importance, but also to recognise the ways in which external social factors can influence them.

RECOMMENDATION SIX

The science curriculum should provide young people with an understanding of some key ideas-about-science, that is, ideas about the ways in which reliable knowledge of the natural world has been, and is being, obtained.

PRACTICAL WORK IN A SCHOOL laboratory can provide contexts for learning some of these ideas-about-science. But, in our view, it cannot provide all that is required. For instance, case studies of some historical and contemporary issues involving science will also be necessary so that pupils can improve their appreciation and understanding of the complex relationships between evidence and explanation, and the complexities of applying scientific knowledge in real-world situations. We recognise, however, that if these aspirations are to be realised, then the learning targets in this area need to be clearly specified, and the assessment framework needs to give proportionate weight to these aspects of science learning. So we have set out a list of such targets on the following pages. We will return to the assessment implications later in this report.

The ideas-about-science represent a significant expansion of the range and depth of treatment that such issues currently demand in the existing curriculum. Their development needs to be undertaken in collaboration with science teachers so that their introduction is a managed process and not a sudden, and possibly unwelcome, event.

5.3 INTEGRATING VARIOUS ASPECTS OF THE CURRICULUM

It is essential that the different elements of the science curriculum discussed in section 5.2 are integrated into a coherent programme. In order to see how this might be done, and to communicate our ideas and aspirations clearly to teachers and others, it may be necessary to develop something more akin to a syllabus, as regards its detail and layout. One very fundamental reason for doing this would be to check that it is indeed possible to integrate all the elements we consider important into a single programme which could reasonably be taught in a series of lessons, following each other in time. In other words, developing a syllabus based on the general ideas outlined above is an important step in testing, and refining, those ideas.

A syllabus would, however, have some further advantages. It would set some intermediate targets for the curriculum, making clear what parts of the curriculum might be covered by each of a number of significant age points, and the depth of

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Young people need some understanding of the social processes internal to science itself, which are used to test and scrutinise knowledge claims before they can become widely accepted.

Ideas-about-science

Through their study of science from 5–16, pupils should come to see science as a search for reliable explanations of the behaviour of the natural world. Their understanding of science should come from:

- evaluating, interpreting and analysing both evidence which has been collected first-hand and evidence which has been obtained from secondary sources;
- hearing and reading stories about how important ideas were first developed and became established and accepted;
- learning how to construct sound and persuasive arguments based upon evidence;
- considering a range of current issues involving the application of science and scientific ideas.

AMONGST THE THINGS THIS WOULD INVOLVE ARE THE FOLLOWING:

At Key Stage 1 and Key Stage 2, pupils should:

- begin to appreciate the value of measurement of quantities as a means of making a more precise record of events and processes;
- learn how to make simple comparisons between objects, materials and events, recognising the need to keep factors other than the one under investigation constant (making a 'fair test');
- become familiar with examples of scientific work which involve careful measurement and recording over a period of time (e.g. weather monitoring; testing water quality);
- read some non-fiction accounts of how new ideas were 'discovered', which illustrate the importance of evidence in convincing others (e.g. the circulation of the blood, microbes as the carriers of infectious diseases).

***In the early years of secondary school*, pupils should learn, through their own practical work and in other ways:**

- that no observation or measurement can ever be sure of matching exactly the 'true' value – that there is always some uncertainty;
- that repeating measurements and taking an average is a good method for reducing the effect of random error;
- to recognise, where appropriate, processes as an interaction between variables;
- how to design a simple investigation of the relationship between two variables, keeping other variables and factors constant;
- how to state in words the pattern of relationship shown by a line or bar graph.

Pupils should also become familiar with stories about the development of important ideas in science which illustrate the following general ideas:

- that scientific explanations 'go beyond' the available data and do not simply 'emerge' from it but involve creative insights (e.g. Lavoisier and Priestley's efforts to understand combustion);
- that many scientific explanations are in the form of 'models' of what we think may be happening, on a level which is not directly observable;
- that new ideas often meet opposition from other individuals and groups,

sometimes because of wider social, political or religious commitments (e.g. Copernicus and Galileo and the Solar System);

- that any reported scientific findings, or proposed explanations, must withstand critical scrutiny by other scientists working in the same field, before being accepted as scientific knowledge (e.g. Pasteur's work on immunisation).

By considering some current issues involving the application of science, pupils should:

- recognise that innovations may have both benefits and risks, including some risks which are unforeseen;
- begin to appreciate that decisions about appropriate solutions to problems are influenced by a range of considerations (including technical feasibility, economic cost, social and environmental impact, ethical implications, and political and religious commitments) and that these may differ in different contexts.

***As pupils progress into Key Stage 4,* they should broaden their understanding of the general ideas outlined above, by seeing how they apply to a wider range of situations and cases. In addition, they should:**

- appreciate that a correlation between two variables does not necessarily mean that one causes the other;
- be able to design well-controlled investigations of situations involving several independent variables;
- recognise that the variation in repeated measurements of a quantity give an indication of the reliability of the measurement.

Pupils should become familiar with stories about the development of important ideas in science which illustrate the following general ideas:

- evidence is often uncertain and does not point conclusively to any single explanation;
- if an explanation predicts an event which would otherwise be unexpected, and this is then observed, this greatly increases our confidence in the explanation (e.g. Adams' predictions of the existence of Neptune);
- that scientific progress can depend on careful and painstaking work, and also on creative conjecture (e.g. the roles of Franklin and of Watson and Crick in establishing the structure of DNA).

By considering some current issues involving the application of science, pupils should:

- recognise that a person's views may be influenced by their professional and/or social affiliations;
- appreciate that many things which we would like to understand cannot (yet) be explained fully in terms of a predictive theoretical model; because of the complexity of the systems involved, the best we can do is to identify correlations between possible factors and the *probability* of a certain outcome (such as the links between smoking and lung disease, or between saturated fat consumption and heart disease);
- understand the ideas of probability and risk;
- be aware of the range of factors which can influence people's willingness to accept specific risks;
- be able to distinguish between technical issues (what is possible) and ethical issues (what ought to be done) when considering issues involving science and technology.

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treatment expected by this age. For some 'explanatory stories', we might want to identify more elementary versions of all or part of the 'story', which would be covered at an earlier stage, to be followed later by additional teaching to develop understanding of the whole 'story'. For others, early work might be of a more preparatory nature, putting in place some of the background knowledge needed before the teaching of the 'story' could proceed.

We see the development of more fully articulated versions of the curriculum as an important stage in the development of any future curriculum proposal. We would, however, want any more detailed specification to be seen as a 'sample scheme', showing one possible way of covering the material of the curriculum, but not claiming to be the only way. Our own recommendations are offered only as a framework on which the curriculum cloth must be hung, and our examples are simply to provide some illustration of our intent and meaning, and not as ideas which we have had insufficient time to fully determine or complete.

5.4 TEACHING APPROACHES

ONE OF THE MAJOR DIFFICULTIES with the current science curriculum, which we identified earlier in this report, is the lack of sufficient variety in the kinds of activities in which learners engage. We feel, therefore, that it is important to emphasise our view that the science curriculum of the future should have much greater variety, not only in the types of learning activity involved but also in the pace of learning. Any science curriculum which is essentially a list of concepts is bound to be content-focussed. If the accompanying modes of assessment have a similar narrow focus, then the combination will force some teachers into a rigid transmissive mode of teaching. One unfortunate consequence is a denial of opportunities for pupils to conduct extended pieces of work exploring aspects of the history of science, or to examine media reports of socio-scientific controversies which report aspects of contemporary science, risk and controversy.

Seeing the science course as a series of short periods of more intensive learning of new ideas (using a range of methods including teacher exposition, practical work, video resources, computer software, reading about science, CD-ROMs, the Internet and so on), alongside more extended periods in which these ideas could be developed and consolidated, would, we believe, result in better learning by more young people. Such a model of working has become familiar to many secondary teachers through their experience of GNVQ courses and is already familiar to primary teachers through the use of topic-based work. This approach would enable pupils to learn and to practise their skills in locating and interpreting information; in evaluating

RECOMMENDATION SEVEN

The science curriculum should encourage the use of a wide variety of teaching methods and approaches. There should be variation in the pace at which new ideas are introduced. In particular, case-studies of historical and current issues should be used to consolidate understanding of the 'explanatory stories', and of key ideas-about-science, and to make it easier for teachers to match work to the needs and interests of learners.

Our view is that the science curriculum of the future should have much greater variety, not only in the types of learning activity involved but also in the pace of learning.

evidence and constructing arguments of their own; presenting their ideas in written and oral form; and defending their conclusions. Such work would recognise the central role of writing as a means of learning ideas, and not solely as a means of producing a record of work done.

This balance between ideas-acquisition and ideas-development-and-consolidation would also make it significantly easier for teachers to provide a range of tasks, better matched to individual pupils' current capabilities and their interests, allowing more purposeful and effective differentiation within a common curriculum than is possible at present.

We recognise that this will, however, only happen in practice if the assessment framework supports and encourages it, by giving appropriate weight to the products (and processes) of these periods of more extended study. As long as summative assessment continues to reward disproportionately the kinds of learning which are best achieved by a narrow range of rather uninspiring and dull classroom activities, then we see little prospect of genuine improvement in the quality of our science education, or in the enjoyment of teachers in teaching it, and learners in learning it.

Assessment should exert a positive and benign influence on the teaching and learning of science.

6 ASSESSMENT

IT IS OUR STRONGLY HELD VIEW that significant curriculum change is unattainable without integral development of new and appropriate models of assessment.

First, with reference to assessment used for *diagnostic* and *formative* purposes, we believe that there is compelling evidence that its systematic use by teachers is an integral part of teaching that can have a very significant positive effect on achievement. Any contemporary science curriculum, therefore, will require the development of tools to aid teachers to use formative assessment to monitor and improve pupils' learning and sense of achievement.

With regard to assessment used for *summative* purposes, the critical principle that must guide any assessment framework adopted for the science curriculum, and the assessment tools used, must be that assessment should exert a positive and benign influence on the teaching and learning of science. That is, the form of any summative assessment should be such as to encourage teachers and pupils to focus more clearly on the most important aspects of learning science, and to spend time on activities which are clearly related to the aims stated on page 12.

Moreover, the assessment system should encourage the development of skills and capabilities which will be required for future employment in the 21st century. That is, rather than emphasising the recall of specific, detailed and unrelated 'facts', any new framework should give greater weight to an assessment of a holistic understanding of the major scientific ideas and a critical understanding of science and scientific reasoning. More attention, therefore, should be devoted to the assessment of those skills and competencies that are required in adult life both at work and for 'lifelong learning' – that is, the ability to read and assimilate scientific and technical information and assess its significance.

IN THIS APPROACH, the emphasis is not on how to 'do' science or create scientific knowledge, or to recall it briefly for a terminal examination. Rather, it is on demonstrating a working familiarity with the major ideas of science, the confidence to use these ideas to communicate with a variety of audiences, and the ability to assimilate and appraise presented information. Such a science education should seek to develop – and should therefore assess – the ability to 'read' and understand the language and arguments of science in a 'critical', 'educated' way. Students should thus be asked to demonstrate the capability to assess the reliability and validity of evidence, to distinguish evidence from explanations, to identify obvious gaps in evidence or reasoning, and to appraise the level of confidence to be ascribed to any claims advanced.

RECOMMENDATION EIGHT

The assessment approaches used to report on pupils' performance should encourage teachers to focus on pupils' ability to understand and interpret scientific information, and to discuss controversial issues, as well as on their knowledge and understanding of scientific ideas.

Rather than emphasising the recall of specific, detailed and unrelated 'facts', any new framework should give greater weight to an assessment of a holistic understanding of the major scientific ideas and a critical understanding of science and scientific reasoning.

Hence, the new instruments for the assessment of pupils' scientific knowledge should:

- reduce the current emphasis on assessing pupils' ability to recall discrete and specific components of their knowledge;

- increase the emphasis on assessing pupils' ability to use their understanding of the major 'explanatory stories' of science;

- assess performances and competencies likely to be required in adult life (such as the ability to comprehend media reports, or to argue a rational case based on data).

The type of assessment that we feel would be more appropriate to the curriculum that we wish to see delivered are questions which require the following competencies.

a The interpretation of media reports of science
Short pieces extracted (and possibly modified) from newspapers should be used to assess whether pupils understand the scientific content of the piece; whether they can identify and evaluate the quality of the evidence presented for the claims advanced; whether they can offer well-thought-out reactions to the risks to which they or others might be exposed; and finally, whether they can give their opinion about future action which should be taken by individuals, government or other bodies.

b Demonstration of an understanding of the major explanatory stories of science
Questions should seek to examine, for instance, whether pupils have understood what the particle model of matter is; whether they can give a short account of it; whether they can use it to explain everyday phenomena; and whether they can explain why it is an important idea in science.

c An ability to ask and answer questions based on data
Such questions should assess pupils' ability to represent data in a variety of ways (notably graphically); to formulate and interpret the messages which can be extracted from data; and to detect errors and dishonesty in the way data are presented or selected. The ability to manipulate and interpret data is a core skill which is of value, not only in science, but in a wide range of other professions and contexts.

d An ability to recognise the role of evidence in resolving competing arguments between differing theoretical accounts
At the heart of scientific rationality is a commitment to evidence. Contemporary science confronts the modern citizen with claims that are contested and uncertain. Questions based on historical or contemporary examples can be used to investigate pupils' understanding of evidence in determining the significance of scientific claims.

It is our view that such items place emphasis more appropriately – on the general skills and competencies that we would expect young people to develop through science

In primary science we might assess pupils' abilities to make presentations in their own words of science ideas, for example through posters, or oral presentations to their teacher or their peers.

education. They ask for a broad familiarity with the fundamentals of science and its historical development. Whilst it is possible for such items to be included in summative tests, many will only provide valid assessments of students' knowledge and understanding when there is an opportunity to read around the topic, conduct research, and write thoughtfully without the pressure of time constraints. The product can then be presented for internal assessment. This sort of work also provides opportunities for much needed variation in the pace of learning in the classroom, allowing time for reflection and consolidation of understanding.

Moreover, such competencies will only be developed by providing sustained and systematic opportunities to develop these skills throughout the curriculum from age 5–16. In primary science we might assess pupils' abilities to make presentations in their own words of science ideas, for example through posters, or oral presentations to their teacher or their peers. Such work might involve re-telling explanations of phenomena or events which had been discussed in class, or stories about scientific work, or the work and thinking of 'great scientists'. Pupils' ability to present evidence could also be assessed, and their ability to use it to make a case, for example, that two things are related; or that something has changed in some way over time or as a result of a specific intervention; or that something causes something else to happen. Assessment should also attempt to see if pupils can understand not only what an idea is but why it is important too – for instance, that knowing about the parts of the human body and how they work may help us to repair them, or that knowing about the behaviour of electricity means that we can build circuits to perform a whole range of useful tasks.

In considering assessment, it is essential to put the horse before the cart – that is, the curriculum and its outcomes before the modes of assessment. But it is equally important to recognise that assessment can play a positive role by helping curriculum planners to become clearer about their real goals. First, by forcing consideration of the question: 'What should pupils be able to *do* when they have completed their study of this curriculum?', and second, by influencing the emphasis of the curriculum implemented in the classroom. It is our view that many of the aspects of young people's knowledge and understanding that we would wish to see developed through the science curriculum require assessment based on coursework of an extended nature. Undoubtedly such assessment, if wrongly applied, could place an additional burden on teachers. However, its use enhances rather than diminishes the role of teachers' professional judgement and authority, both of which have been undermined by the developments of the past decade. There is sufficient international evidence to show that there are mechanisms, such as moderation by peer review, which can establish and sustain the sort of professional culture which can enable reliable and consistent judgements of the quality of learners' work to be made.

We should also attempt to see if pupils can understand not only what an idea is but also why it is important.

7 TOWARDS CHANGE

IN THIS REPORT WE HAVE ADVANCED a case for a fundamental change in the nature of the science education offered to the nation's youth. We are not, of course, the first group to advance a case for change or to seek to implement it. The history of school science is punctuated with attempts at reform, amongst which are the Nuffield courses of the 1960s, the Science, Technology and Society (STS) courses and the Secondary Science Curriculum Review of the 1970s and 1980s and, more recently, the introduction of investigative science in Attainment Target Sc1. All of these exemplify the problems encountered by attempting to change either *what* is taught in science or *how* it is taught. Santayana's comment that 'those who forget history are condemned to repeat the mistakes of the past' is, perhaps, particularly apt here. Whilst all efforts at reform have enjoyed some measure of success, their clear message is that change is a slow process which must be both carefully managed and supported. For innovation can have unexpected negative consequences as well as their intended positive ones.

In this report we have set out our vision of the sort of science education we would wish to see in the 21st century. We recognise, however, that this is a long-term aim that will have to be approached gradually and with the involvement of practising teachers. Therefore the sorts of changes this report envisages need to be tried out and evaluated. This leads us to make two sets of arguments for change – in the first instance for small changes in the short to medium term, and second, for the establishment of a set of structures and processes which would enable a managed process of curriculum development and evaluation. Whilst some change in the near to immediate future is needed, it is the long-term considerations that we regard as of greater importance.

7.1 CHANGES REQUIRED IN THE SHORT TERM

The past nine years have seen a set of major changes and innovations in the education system. Science teachers and schools have had to contend with the introduction of a National Curriculum which has been revised twice, and a new system of inspection and monitoring which many have found alienating and threatening. In addition, the introduction of competitive league tables, greater parental choice and, more recently, benchmarking and target-setting have been an additional burden. To their credit, teachers have shown considerable resilience and flexibility in adapting and evolving to meet the new context in which they operate. Whilst there are some signs emerging of a dissatisfaction at the growing gap between science as taught in schools and science as experienced in society, we sense that the majority of teachers need a sustained period of stability in which they can refine, reflect and develop their practice within a framework that is relatively constant and secure.

Therefore, we would see moves towards the kind of science curriculum outlined in this report as a medium to long term aim, and would wish to argue for only three immediate changes to the existing science curriculum.

The majority of teachers need a sustained period of stability in which they can refine, reflect and develop their practice within a framework that is relatively constant and secure.

FIRST, AS WE HAVE ARGUED in section 4.3, the lack of a well-defined sense of purpose needs remedying by a document which articulates succinctly the aims of teaching science. Such a rationale must be comprehensible to pupils and parents. Their existing omission is an abdication of our responsibility as a society to justify to our teachers of science why we require the content of the document to be provided for all the nation's youth. It forces teachers to make their own interpretations of the document, and inevitably to steer in different directions which, in itself, undermines the purpose and function of a National Curriculum to achieve a homogeneity and consistency of experience.

Second, we would argue for an amalgamation of the components 'Experimental and Investigative Science' (Sc1) and some aspects of the 'General Requirements' (Sc0) which are both elements of what we see as ideas-about-science. Currently the latter is largely seen as extraneous and, because it is only assessed minimally, little time is devoted to teaching aspects of science which we consider vitally important to the understanding of science required by future citizens. The substantive incorporation of these two into one attainment target would give more formal recognition to the importance of these aspects of science. It would also address the criticism that Sc1 over-emphasises the role of a particular, and fairly narrowly defined, type of empirical practical work in communicating an understanding of the practices of science.

Finally, we do not believe that the existing forms of assessment are sufficiently representative of the skills and competencies that society wishes science education to develop. We would therefore urge strongly the introduction of new types of assessment – for instance, a comprehension exercise requiring pupils to interpret and comment on media reports about science. This change would go some way to fulfilling our second important objective – that of encouraging those skills and competencies that society wishes science education to develop in its future citizens.

RECOMMENDATION NINE

In the short term:
The aims of the existing science National Curriculum should be clearly stated with an indication how the proposed content is seen as appropriate for achieving those aims.

Those aspects of the general requirements which deal with the nature of science and with systematic inquiry in science should be incorporated into the first Attainment Target 'Experimental and Investigative Science' to give more stress to the teaching of ideas-about-science; and new forms of assessment need to be developed to reflect such an emphasis.

7.2 TOWARDS A FRAMEWORK FOR INNOVATION AND DEVELOPMENT OF THE SCIENCE CURRICULUM

One of the problems of a statutory national framework for the curriculum is that it makes innovation – whether by individual teachers or schools, or groups of schools, or larger organisations – more difficult. It totally inhibits the possibility of innovation and experimentation at the periphery within individual schools. Hence curriculum development then becomes the responsibility of the centre – in our case the Qualifications and Curriculum Authority. When changes are introduced in the statutory

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National Curriculum framework, as happened in 1991 and 1995, the new features are, inevitably, untested, as there is no mechanism which allows significant ideas to be trialled and evaluated prior to their introduction more generally. The history of 'Experimental and Investigative Science' (Sc1) is a case in point, where many of the problems encountered by pupils, teachers and examiners might have been reduced had there been an opportunity to pilot the teaching approaches and assessment methods envisaged on a restricted scale prior to national implementation.

Essentially, the fundamental problem for the current system, which is not unique to science education, is that there exists no mechanism for systematically encouraging innovation and curriculum development. Indeed, the climate of league tables, inspections and National Curriculum tests is a significant disincentive to any school or individual to step outside the normal framework of provision. To borrow an evolutionary metaphor, the existing National Curriculum framework does not encourage adaptation and the growth of diversity. New forms cannot evolve and be tested to see if they offer improvement. As a result, the system cannot easily accommodate to any changes in the societal context which may require a different set of competencies and skills compared with those fostered by existing curricula. Although the structure does allow for schools to apply for disapplication (that is, for permission not to have to follow the National Curriculum in a particular subject), to date only a handful of schools have applied and none has been granted permission. In short, no system can evolve without innovation, *which must be systematically encouraged*.

RECOMMENDATION TEN

In the medium to long term:
A formal procedure should be established whereby innovative approaches in science education are trialled on a restricted scale in a representative range of schools for a fixed period. Such innovations are then evaluated and the outcomes used to inform subsequent changes at national level. No significant changes should be made to the National Curriculum or its assessment unless they have been previously piloted in this way.

CONSEQUENTLY, our final recommendation is that a formal procedure be established for the testing and trialling of innovation, with appropriate safeguards and controls, and with adequate mechanisms for monitoring and evaluation. We would see such a procedure applying to all significant innovations and not only to those which might arise from the recommendations of this report. We are making here a general recommendation about the management of curriculum change, changing the nature of the National Curriculum review from a series of successive *events* to a continuous and managed *process*.

Having set out in this report our recommendations for the future of the science curriculum, the next step, in our view, is to work out with others the implications of the approach we are advocating in greater detail, as a more detailed programme of study, with appropriate assessment methods and instruments. A selection of schools of varying kinds – comprehensive, independent, grammar – should then be invited to participate in trials of such an approach over a period of several years, and the outcomes evaluated. Only from such a programme of development, trialling

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and evaluation can a curriculum and teaching materials emerge which are both practicable (that is, well-adapted to the environment in which they must be used) and valued by their users and by society as a whole. Such practices are used in other European countries. Whilst recognising that curriculum development, piloting and evaluation are expensive, the lesson of history is that other approaches to change are even more expensive. Without such a mechanism for change, the failings of the science curriculum in meeting the needs of a modern society will lead to a growing disjunction between the aspirations of young people for a meaningful and relevant science education and that which is provided. The consequent alienation of science from society and of society from science is a price we cannot afford to pay.

APPENDIX 1: Attendees at closed seminars

The closed seminars were attended by approximately twenty leading individuals working in science education in the UK, including school and university teachers and representatives of QCA, OFSTED and The Royal Society. This group attended all the seminars. In addition, other individuals with specialist expertise were invited to contribute to specific seminars.

Dr Derek Bell *Liverpool Hope University College*
Helen Churchill *Vyners School, Hillingdon*
Dr Mike Coles *Institute of Education/QCA*
Professor Rosalind Driver *King's College London*
Esmé Glauert *Institute of Education*
Andrew Hunt *Nuffield Curriculum Projects Centre*
Dr John Leach *University of Leeds*
Professor Robin Millar *University of York*
Bryan Milner *Examiner, NEAB/textbook author*
Patricia Murphy *Open University*
Mick Nott *Sheffield Hallam University*
Professor Jon Ogborn *Institute of Education/Institute of Physics*
Dr Jonathan Osborne *King's College London*
Gary Phillips *Science Adviser, Croydon*
Bob Ponchaud *Her Majesty's Inspectorate*
Rev Dr Michael Reiss *Homerton College Cambridge*
Professor Joan Solomon *Open University/King's College London*
Dr Mary Ratcliffe *University of Southampton*
Helen Reynolds *Gosford Hill School, Oxford*
Carolyn Swain *Qualifications and Curriculum Authority*

ADDITIONAL ATTENDEES
Seminar 1:
Professor Paul Black *King's College London*
Jill Nelson *Royal Society*
Professor Alan Smithers *Brunel University*
Professor Mike Pilling *University of Leeds*
Seminar 2
Professor Edgar Jenkins *University of Leeds*
Jill Nelson *Royal Society*
Professor Stephen Norris *Memorial University of Newfoundland, Canada*
Dr Clive Sutton *University of Leicester*
Professor Wynne Harlen *Scottish Council for Research in Education*
Seminar 3
John Holman *Headmaster, Watford Grammar School*
Robert Rees *Royal Society*
Seminar 4
Professor Mike Atkin *Stanford University, California*
Professor Paul Black *King's College London*
Robert Rees *Royal Society*