Principles and big ideas of science education

Edited by Wynne Harlen

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This report, developed by a group of ten international experts in science education following the Purkwa Loch Lomond seminar in October 2009, sets out the principles that should underpin the science education of all students throughout their schooling.

It argues that students should be helped to develop 'big ideas' *of* science and *about* science that will enable them to understand the scientific aspects of the world around and make informed decisions about the applications of science.

For this understanding students need learning experiences that are interesting and engaging and seen as relevant to their lives. The report therefore also considers the progression from small ideas about specific events, phenomena and objects to more abstract and widely applicable ideas and the significant aspects of pedagogy that are required to support this progression.

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Preface

In October 2009 a small international seminar was held with the aim of identifying the key ideas that students should encounter in their science education to enable them to understand, enjoy and marvel at the natural world. The motivation for the seminar was the realisation that students' science education across primary and secondary schooling, with few exceptions, lacked coherence and any notion of progression towards overarching ideas that it is important for children to learn. Although teams developing various national curricula, guidelines and standards have wrestled with problems of content selection, it often appears that a focus on specific topics obscures the overall ideas being developed – a matter of not seeing the wood for the trees. However, it is not just a problem of form but also of substance; what we teach owes more to history than to new thinking.

The seminar participants – some practising scientists and engineers, others science educators of long standing – are all concerned with improving school science education not only in their own countries but internationally. The brief profiles of the participants given at the end of the report indicate the range of expertise they brought to the seminar. The willingness, even eagerness, of these extremely busy people to give up their time to travel to Scotland and to write or collect papers in preparation for the seminar, was convincing evidence, had it been necessary, that there was an important job to be done.

The seminar was made possible by the award of the 'Purkwa' prize, given by the French Academy of Sciences and the Saint Etienne Mining School. It took place at a conference venue on the shore of Loch Lomond for two-and-a-half days. Work continued after the seminar by correspondence and gradually the material in this report was created from the comments, amendments and additions by the members of the group. It is truly a joint product of those taking part for which gratitude is due to: Derek Bell, Rosa Devés, Hubert Dyasi, Guillermo Fernández de la Garza, Pierre Léna, Robin Millar, Michael Reiss, Patricia Rowell, Wei Yu, and Juliet Miller, who kept the record during the seminar and has been responsible for the lay-out of this report.

Wynne Harlen

Duns, July 2010

Ten principles of science education

1 Throughout the years of compulsory schooling, schools should, through their science education programmes, aim systematically to develop and sustain learners' curiosity about the world, enjoyment of scientific activity and understanding of how natural phenomena can be explained.

2 The main purpose of science education should be to enable every individual to take an informed part in decisions, and to take appropriate actions, that affect their own wellbeing and the wellbeing of society and the environment.

3 Science education has multiple goals. It should aim to develop:

- understanding of a set of 'big ideas' in science which include ideas *of* science and ideas *about* science and its role in society
- scientific capabilities concerned with gathering and using evidence
- scientific attitudes.

4 There should be a clear progression towards the goals of science education, indicating the ideas that need to be achieved at various points, based on careful analysis of concepts and on current research and understanding of how learning takes place.

5 Progression towards big ideas should result from study of topics of interest to students and relevance in their lives.

6 Learning experiences should reflect a view of scientific knowledge and scientific inquiry that is explicit and in line with current scientific and educational thinking.

7 All science curriculum activities should deepen understanding of scientific ideas as well as having other possible aims, such as fostering attitudes and capabilities.

8 Programmes of learning for students, and the initial training and professional development of teachers, should be consistent with the teaching and learning methods required to achieve the goals set out in Principle 3.

9 Assessment has a key role in science education. The formative assessment of students' learning and the summative assessment of their progress must apply to all goals.

10 In working towards these goals, schools' science programmes should promote cooperation among teachers and engagement of the community including the involvement of scientists.

Fourteen big ideas in science

Ideas *of* science

1 All material in the Universe is made of very small particles.

2 Objects can affect other objects at a distance.

3 Changing the movement of an object requires a net force to be acting on it.

4 The total amount of energy in the Universe is always the same but energy can be transformed when things change or are made to happen.

5 The composition of the Earth and its atmosphere and the processes occurring within them shape the Earth's surface and its climate.

6 The solar system is a very small part of one of millions of galaxies in the Universe.

7 Organisms are organised on a cellular basis.

8 Organisms require a supply of energy and materials for which they are often dependent on or in competition with other organisms.

9 Genetic information is passed down from one generation of organisms to another.

10 The diversity of organisms, living and extinct, is the result of evolution.

Ideas *about* science

11 Science assumes that for every effect there is one or more causes.

12 Scientific explanations, theories and models are those that best fit the facts known at a particular time.

13 The knowledge produced by science is used in some technologies to create products to serve human ends.

14 Applications of science often have ethical, social, economic and political implications.

Introduction

Why Big Ideas?

The recognition that all students should leave school with a basic understanding of the ideas and procedures of science is now widespread, even universal. Yet we find, at least in developed countries across the world, a decline in young people taking up studies in science and other signs of lack of interest in science. Students are widely reported as finding their school science not relevant or interesting to them. This is certainly their perception of it, whatever the reality. They appear to be lacking awareness of links between their science activities and the world around them. They 'don't see the point' of studying things that appear to them as a series of disconnected facts to be learned. In practice, the only point that they can discern is that they need to pass examinations. Whilst tests and examinations do indeed have a role in creating the present situation they are not the only cause.

Current curricula, even those developed in the past two decades, have their roots in history. Each reform is influenced by what went before and it is not so long ago that science was optional for students at about the age of 14 and secondary school science was seen as having been designed for those who would go on to specialise in science rather than for all students. Although science education is now recognised as being important for all throughout their compulsory schooling, it is hard to shake off the traditional image. It is little wonder, then, that current school science leaves many students untouched in respect of developing broad ideas of science that could help their understanding of things around them and enable them to take part in decisions as informed citizens of a world where science and technology are of ever increasing significance.

The plea for relevance is most often to be heard from students at secondary school level, where ideas to be learned are becoming more abstract than those encountered in primary school science. But the course of learning in science requires a progressive grasp of ideas that have wider application and hence are inevitably more abstract. Problems of understanding arise when these abstract ideas do not seem to be rooted in and connected to the more concrete experiences from which they should be built.

At the primary level, activities generally begin from objects and events around; the context gives them reality and teachers strive to ensure that they are of interest to the children. The problem there is not so much lack of relevance as perceived by the children but the relevance of what they

Current school science leaves many students untouched in developing broad ideas of science that could help understanding of things around them and enable them to take part in decisions as informed citizens

The goal of science education is not knowledge of a body of facts and theories but a progression towards key ideas which enable understanding of events and phenomena of relevance to students' lives

learn to building understanding that is useful not just for their secondary education but for the rest of their lives. There is an enormous range of possible topics and activities. How are teachers to choose those that make the best use of limited and precious learning time?

Part of the solution to these problems is to conceive the goals of science education not in terms of the knowledge of a body of facts and theories but a progression towards key ideas which together enable understanding of events and phenomena of relevance to students' lives during and beyond their school years. We describe these as 'big ideas' in science and in this report try to explain what we consider them to be, how they can be selected and how best communicated. The mode of communication is crucial if we are to convey the links between ideas and experience, which is better preserved in narrative form than in a list of disconnected points. It is important also to show how ideas have their roots in children's early explorations so that teachers, even if not the children, are aware of the contribution of these activities to a developing picture of the scientific aspects of the world around.

Big ideas across the curriculum?

It is not only science education than can be improved by anchoring facts and figures to unfolding themes. Historians are calling for specific events to be linked to narratives; similarly there is a strong case for bringing together ideas from studying different phenomena in geography. The same could be said of many domains of knowledge, which exist as domains by virtue of possessing a core of knowledge, skills and attitudes but where, as in the case of science, the nature of this core is not made explicit. To express it in terms of the development of big ideas would surely provide a rationale and a framework for inclusion of particular topics and types of study within the school curriculum.

High stakes assessment

There can be no doubt that a reason for the current fragmentation of students' learning experiences in many domains is to be found in the form of assessment that is used. Conventional tests and examinations ask a series of disconnected questions which inevitably represent a selection, from the possible range, of those questions which can be reliably scored. Not surprisingly this encourages teaching of disconnected items of knowledge and how to give the 'right' answers. Further, the use of the results of assessment for high stakes decisions affecting students and teachers has implications for what is assessed and how. When students and teachers are being judged on results of tests or examination, there is a premium on accuracy that leads to restricting what is included to learning outcomes where performance can be most easily marked as correct or

incorrect. This tends to exclude outcomes that are more difficult to judge unequivocally as right or wrong, such as application of concepts, reasoning, understanding (as opposed to factual knowledge) and attitudes that are likely to influence future learning. Although some of the outcomes that are difficult to include in formal written examinations can be assessed through projects or course work, high stakes pressure leads to a narrow focus in such work on the aspects that are reflected in the assessment criteria. This 'disease' spreads to the primary school when testing is frequent and is used as a measure of teachers' or schools' performance.

High stakes assessment results in what is taught being determined by what is assessed rather than by what is of value in adding to a growing understanding of key ideas and development of reasoning skills and attitudes

In extreme, this results in what is taught being determined by what is assessed rather than by what is of value in adding to a growing understanding of key ideas and development of reasoning skills and attitudes. It causes teachers to teach in a way that neither pleases them nor satisfies their students. Unfortunately policies of frequent external testing of all children persist, despite two decades of research which has given evidence of their negative impact and refuted the claim that 'testing raises standards'. However, it is not our purpose here to discuss further issues relating to assessment of students' achievement nor the related matter of how to evaluate the effectiveness of schools, except to point out that it is high time for considerable investment in developing new approaches to assessment that better reflect key ideas and skills in all subject domains.

Recent reforms of pedagogy in science education

Recent actions to reverse students' lack of interest in and enjoyment of science have focused on the approach to teaching. An inquiry-based approach is widely advocated and is being implemented in many different countries across the globe. Inquiry, well executed, leads to understanding and makes provision for regular reflection on what has been learned, so that new ideas are seen to be developed from earlier ones. It also involves students working in a way similar to that of scientists, developing their understanding by collecting and using evidence to test ways of explaining the phenomena they are studying. There is growing evidence that this has a positive influence on attitudes to science. However, it is optimistic to assume that change in pedagogy can be brought about without changing content or the curriculum. Inquiry-based teaching is demanding, both of teachers' skill and of time for teaching and learning. Inquiry-based learning can lead to greater depth in understanding but as it takes more time the corollary is that the breadth has to be reduced. Thus identifying big ideas in science is a natural, and indeed necessary, accompaniment to promoting inquiry-based science education.

Identifying big ideas in science is a natural accompaniment to promoting inquiry-based science education

Identifying big ideas in science

There have been many other attempts to set out big ideas in science, so it is fair to ask: why add to what is already available? One reason is that none of the existing lists quite fits our purpose; another, that it is important not only to set out the emerging ideas but to give the rationale and the thinking behind them. Furthermore, ensuring that students are developing their understanding through inquiry reinforces the necessity of identifying the course of cognitive progression.

In relation to purpose, the intention of the seminar and the subsequent work leading to this report was to describe not just the ideas to be achieved by the end of compulsory schooling but the ideas that need to be achieved to make progress towards them. This required decisions about the nature of progression and how it might be expressed. It was necessary to address questions about how the course of progression is to be identified – by the logic of how one idea depends on another, or on the evidence of students' ideas found at various stages, or both? – and questions about how to express progression without losing the link with the overall idea.

To set out our rationale we began the task by stepping back from identifying possible nominations for big ideas to consider the principles that ought to guide our answers to the many questions about the goals and procedures of science education. Identifying big ideas would mean nothing unless it excluded as well as included material currently taught. Thus decisions need to be based on explicit and principled reasons. We considered principles at the start of the seminar and returned to review them at its conclusion. The intervening sessions, each led by one of the participants, covered the conception of big ideas, the criteria for selection, the study of some examples and existing frameworks, the nature of progression and the pedagogy appropriate to the principles and the development of broad understanding of scientific ideas and the nature of scientific activity.

None of these topics was brought to a conclusion during the two-and-a-half day seminar – there was no agreed list of big ideas, for instance – but the work continued during the following months by correspondence. In this report, after setting out ten principles underpinning the science education of all students, we explain the thinking behind the selection of 14 big ideas, ten of which are ideas *of* science and four ideas *about* science. We then consider the question of progress towards achievement of these ideas and some of the implications for classroom practice of working with big ideas in mind.

In reporting the outcomes of the seminar and subsequent work we make no specific references to supporting literature or to similar work of others. It was a deliberate decision not to make reference to other writing to support our views but we nonetheless acknowledge that we have drawn, both consciously and unconsciously, on a very wide range of writing and thinking of fellow authors and researchers. As preparation for the seminar a list of key sources was drawn up, most being already familiar to participants. Other source material was added by participants and more were used in preparing the report. The list of those found most useful and relevant is appended.

Section One

Principles underpinning essential education in science

These statements of principle convey the values and standards which we consider should guide decisions and actions in science education and against which those decisions and actions should be judged. There is no hierarchy in the ways these statements are sequenced, but a rough logic in that they begin with general aims, purposes, goals and progression, followed by principles relating to learning experiences and implications for schools' science programmes.

1 Throughout the years of compulsory schooling, schools should, through their science education programmes, aim systematically to develop and sustain learners' curiosity about the world, enjoyment of scientific activity and understanding of how natural phenomena can be explained.

Science education should enhance learners' curiosity, wonder and questioning, building on their natural inclination to seek meaning and understanding of the world around. Science should be introduced and encountered by school students as an activity that is carried out by people including themselves. Their personal experiences of finding out and of making connections between new and previous experiences not only bring excitement and personal satisfaction but also the realisation that they can add to their knowledge through active inquiry. Both the process and product of scientific activity can evoke a positive emotional response which motivates further learning.

In this context we take 'science' to be multifaceted, encompassing knowledge about the world and the processes of observing, questioning, investigating and reasoning about evidence through which knowledge and theories are developed and changed. Affirming that science, understood in this way, has a key role in education from the start of schooling does not deny the importance of establishing basic numeracy and literacy in the early years of schooling. Language is essential to all learning, and science has a particular role in providing a context and motivation for its development. The communication and discussion of ideas from direct experience requires learners to try to convey meaning to others and leads them to reformulate ideas in response to the meaning that others give to their experiences. Thus, development of language and ideas about the world naturally go together. Similarly, science provides a key context for the development of mathematical skills.

Science should be introduced and encountered by school students as an activity that is carried out by people including themselves

We are not claiming that every concept can be introduced and understood in early education. Understanding in science stems from exploration of objects and phenomena stimulated by curiosity about how to explain things in the world around us and, as noted further below (Principle 4), understanding is not something that is present or absent but progresses in complexity with increasing experience.

The principle that science should be part of primary school education is based on firm evidence of its positive impact. Primary school science challenges children's intuitive non-scientific ideas which, if left unchecked, can interfere with later understanding of the world.

Undertaking scientific inquiry gives pupils the enjoyment of finding out for themselves and initiates appreciation of the power and limitations of science

Undertaking scientific inquiry gives students the enjoyment of finding out for themselves and initiates appreciation of the nature of scientific activity, of the power and the limitations of science. Learning about the people and history of science supports appreciation of science as an important human endeavour in which reliable knowledge is built up through the systematic collection of data and use of evidence.

2 The main purpose of science education should be to enable every individual to take an informed part in decisions, and to take appropriate actions, that affect their own wellbeing and the wellbeing of society and the environment.

'Science education for all' means just that: the education that is important for all learners, both those who may later become scientists or technologists or take up occupations requiring some scientific knowledge and those who may not do so. Education in science serves both the individual and society.

For learners as individuals, science education helps them to develop the understanding, powers of reasoning and attitudes that enable them to lead physically and emotionally healthy and rewarding lives. Understanding aspects of the world around them, both the natural environment and that created through application of science, serves not only to satisfy – and at the same time to stimulate – curiosity but helps individuals in their personal choices affecting their health and enjoyment of the environment as well as for their choice of career. Ways of learning science that lead to understanding can also help to develop learning skills that are needed throughout life in order to operate effectively in a world that is changing rapidly. The development of attitudes towards science and towards the use of evidence in making decisions helps learners become informed citizens, to reject quackery and to recognise when evidence is being used selectively to support arguments in favour of particular actions.

Ways of learning science that lead to understanding can also help to develop learning skills that are needed throughout life in order to operate effectively in a world that is changing rapidly

Equally there are benefits to society if individuals and groups make more informed choices in relation to avoiding, for instance, waste of energy and other resources, pollution and the consequences of poor diet, lack of exercise and misuse of drugs. As well as impact on their own daily lives, these things have wider implications for their and others' future lives through longer-term impact of human activity on the environment. Understanding of how science is used in many aspects of life is needed for appreciating the importance of science and for recognising the attention that needs to be given to ensuring that scientific knowledge is used appropriately. Students need to know how, both currently and historically, technology, using scientific knowledge, can impact both positively and negatively on society. Relating science to familiar situations and objects used daily stimulates interest in learning science but should also be used to develop the realisation of how widespread, locally and globally, are the consequences of its applications.

A greater general awareness of the role of science in daily life, and particularly the more informed attitudes that result from early science education, may well lead to more students choosing to specialise in science, but as a secondary rather than a main aim of 'science for all'.

3 **Science education has multiple goals. It should aim to develop:**

- **understanding of a set of big ideas in science which include ideas *of* science and ideas *about* science and its role in society**
- **scientific capabilities concerned with gathering and using evidence**
- **scientific attitudes.**

Here we are using the term 'idea' to mean an abstraction that explains observed relationships or properties. This is different from the everyday use of the word 'idea' as a thought which is not necessarily based on evidence. A 'big' idea in science is one that applies to a range of related objects or phenomena, whilst what we might call smaller ideas apply to particular observations or experiences. For instance, that worms are well adapted to living in the soil is a small idea; a corresponding big idea is that living things have evolved over very long periods of time to function in certain conditions.

Through science education, students should develop understanding of big ideas about objects, phenomena, materials and relationships in the natural world (for instance, that all matter is made of small particles; that objects are able to affect others at a distance). These ideas not only provide explanations of observations and answers to questions that arise in everyday life but enable the prediction of previously unobserved

phenomena. Science education should also develop big ideas about scientific inquiry, reasoning and methods of working (for instance, that scientific inquiry entails making predictions based on possible explanations and assessing the value of different ideas in relation to evidence) and ideas about the relationship between science, technology, society and the environment (for instance, that applications of science can have both positive and negative social, economic and environmental effects).

The goals of science education also include the development of scientific capabilities and scientific attitudes … their achievement involves the use of language – written, oral and mathematical

Although these big ideas in science form the main focus of this report it is important to note that the goals of science education also include the development of scientific capabilities and scientific attitudes.

Appreciation of how science knowledge is developed should be derived at least in part from experience of undertaking scientific inquiries of different kinds. Through such activity students should develop skills of framing questions and finding ways of gathering data by observation and measurement to answer them, analysing and interpreting data, and engaging in discussion about findings and the process of arriving at them.

Fundamental scientific attitudes include willingness to take part in scientific activities, that is, to inquire and investigate in a scientific way. Goals of science education should include willingness to collect data in a controlled and systematic way, to be open-minded in interpretation of data, to work collaboratively with others, to be questioning and appropriately critical of claims and proposed explanations and, in the course of inquiries, to behave responsibly in relation to the environment and one's own and others' safety and welfare.

These multiple goals are not achieved independently of one another. There is essential interaction among them in learning: *real understanding* requires capabilities, such as are involved in using evidence and in reasoning, and attitudes such as curiosity, respect for evidence and open-mindedness. Their achievement involves the use of language – written, oral and mathematical language – to describe the properties and relationships of objects and phenomena and the recognition of the scientific meaning of words which have a different meaning in everyday usage.

4 There should be a clear progression towards the goals of science education, indicating the ideas that need to be achieved at various points, based on careful analysis of concepts and on current research and understanding of how learning takes place.

Children bring to school ideas formed about the world through their actions, observations and thinking in their daily lives. These are the starting points for the development of the understandings, capabilities and

By finding out how students make sense of experiences, we can provide a rich description of the changes in thinking that indicate progress towards goals

attitudes that are the goals of science education. To help progress towards later goals it is important to know something about the direction and nature of that progress and particularly what students can be expected to know, understand, do and reason about at various points in the course of their school education.

Identifying the course of progress requires both logical analysis to find the simpler ideas that are needed as a basis for more complex ones (for instance, ideas about mass and volume before density) and – since human beings do not necessarily develop ideas logically – empirical evidence from research on how thinking develops. These are not independent approaches, for expectations frame the focus of research questions. However, it is through finding out how students make sense of experiences that we can provide a rich description of the changes in thinking that indicate progress towards the goals.

Scientific ideas are often complex and progress depends variously on expansion of experience, development of reasoning and access to different ways of explaining phenomena, properties and relationships. Progress will therefore vary from student to student according to their opportunities both in and out of school. A precise description of progress, applying to all students, is thus unrealistic but there are common trends that enable a broad description of what might be expected at various points as students move from pre-school, through primary and secondary education. These trends include:

- increasing ability to consider that properties may be explained by features that are not directly observable
- greater recognition that several factors need to be understood if phenomena are to be explained
- greater quantification of observations, using mathematics to refine relationships and deepen understanding
- more effective use of physical, mental and mathematical models.

Recognising and applying such general trends supports a more flexible approach to progression than does a prescribed sequence of activities which may not match the needs of all students, a point taken further in discussing our next principle.

5 Progression towards big ideas should result from study of topics of interest to students and relevance in their lives.

It is important to distinguish between the written document which sets out the curriculum in terms of a sequence of goals for learning (often a ‘national curriculum’) and the classroom activities experienced by learners. The teaching programme is sometimes described as ‘curriculum’ but here

we use the word for the document setting out goals and intentions across the years of schooling. It is not the role of the curriculum document, in this sense, to set out how the goals are to be achieved. This is the role of teachers and of guidance produced by projects or programme developers. Such material exemplifies the learning experiences, contexts and approaches most likely to achieve the goals in Principle 3 and to meet the standards in other principles. It should help teachers provide learning experiences that are seen by students as relevant and important and, above all, motivating. A key question for programme developers and teachers is how to ensure that the 'small' ideas developed from studying particular topics build to form gradually 'bigger' ideas.

Students find it very difficult to learn with understanding from tasks which have no meaning apparent to them

One answer is to use an analysis of the prerequisites of each big idea to create a series of exercises that ought in theory to combine to produce the intended understanding. When faced with structured materials and carefully sequenced activities, students have to trust that 'if you do this today you will understand something tomorrow'. But taking this approach is to ignore much of what is known about how people learn, in particular the importance of making sense of experiences. Learners find it very difficult to learn with understanding from tasks which have no meaning that is apparent to them. They learn more quickly when able to link new experiences to what they already know, when they have time to talk and question and are motivated by curiosity to answer questions. This suggests activities that enable students to engage with real objects and with real problems. It means that programmes of teaching and learning should be sufficiently flexible to allow for differences in experiences and in what particular localities have to offer, so that students' interests and questions are used as starting points in working towards common goals. Such activities are not typically ones that address ideas one at a time as in a structured programme. Activities with meaning and interest for students frequently contribute to the development of several related ideas.

6 Learning experiences should reflect a view of scientific knowledge and scientific inquiry that is explicit and in line with current scientific and educational thinking.

Science is often presented as a collection of facts and theorems that have been proved to be correct. The word 'objective' is frequently used to describe 'the scientific method', implying that there is a single approach and that it is somehow independent of human judgment and values. By contrast, the current view is that science is by no means static; theories are dependent on available evidence and as such may change as new evidence emerges. Science is seen as the result of human endeavour, involving creativity and imagination as well as the careful collection of data and interpretation of data to generate evidence. The history of science provides

Science seen as the creation of understanding about the world is more likely to excite learners than when seen as a set of mechanical procedures and established 'right answers'

many examples of change in how things, for example the solar system, are understood. With hindsight, knowing the evidence that eventually supported the new ideas, these ideas may seem obvious, but at the time they often required a leap of creative thinking that led to the collection of supporting evidence rather than this being the starting point – a mixture of inductive and deductive reasoning. Ideas that are supported repeatedly by evidence acquire the status of 'facts' but their stability depends on extensive evidence. Science seen as the creation of understanding about the world is more likely to appeal to and excite learners than when seen as a set of mechanical procedures and established 'right answers'.

Scientific activity and thinking, whether by pupils or scientists, aims for understanding. In this it differs in its primary emphasis from technology, which aims to solve problems through designing and making products. In developing understanding, the ultimate judgment of scientific validity is evidence from the physical world. In this respect, science differs from mathematics, where logic is the basis of reasoning. There are many reasons for combining science, mathematics and technology in teaching and learning but it remains important to recognise their different contributions to generating knowledge and understanding. Mathematics has the attraction of being precise, giving clear-cut answers. In comparison, science can seem imprecise but this is because it depends on evidence which may be uncertain or open to a range of interpretations, not because it is merely a matter of opinion or unvalidated belief.

7 All science curriculum activities should deepen understanding of scientific ideas as well as having other possible aims, such as fostering attitudes and capabilities.

It is not by accident that the development of big ideas comes first in the list of goals in Principle 3, for this should have priority in designing learning experiences. Many learning experiences in science also contribute to the development of capabilities and attitudes, but activities which have only these non-cognitive goals, and are free of subject matter that can lead to development of scientific ideas, do not contribute sufficiently to science education. Skills must be used in relation to some subject matter: something must be observed; data must be about something. If this 'something' is not related to understanding the physical or living world, the skill being used is generic rather than scientific. Similarly, activities designed only for enjoyment or excitement are no more part of science education than is a firework display.

As with all learning, there are different kinds of motivation for learning science – some intrinsic, arising from interest in the subject and some extrinsic, in the form of excitement or rewards. There is a role for the

attention-grabbing demonstration when it leads to questions that students go on to investigate. However, it is particularly important for primary school teachers to ensure that children's activities go further than enjoyment, and help their growing understanding of things around them. This is not to say that younger learners will necessarily realise the big ideas that their activities are intended to help them to understand; indeed, this is likely only for older secondary students. But in the mind of the teacher there should be conscious awareness of how activities contribute threads of thinking that can eventually be drawn together. At the primary level, where the big ideas may seem particularly remote from children's understanding, teachers may need help in recognising the importance in the progression to big ideas of the smaller ideas that are developed in earlier experiences.

At the primary level, where the big ideas may seem remote from children's understanding, teachers may need help in recognising the importance in the progression to big ideas of the smaller ideas that are developed in earlier experiences

8 Programmes of learning for students, and the initial training and professional development of teachers, should be consistent with the teaching and learning methods required to achieve the goals set out in Principle 3.

Whether or not a learner understands an idea depends on how well it helps him or her to make sense of experiences at a particular time. The process of 'making sense' of new experiences involves using an idea to make predictions which are tested against new evidence gathered through some form of inquiry. There may be several ideas to try, arising from a learner's previous experience or provided by other students, the teacher or sources of information. If students are required to accept ideas, which may well conflict with their intuitive ideas, without this opportunity to 'see for themselves', it is unlikely that the ideas will really be used in making sense of things around them. It follows that the teaching methods required are ones that enable students to build their understanding through making predictions based on possible ideas, collecting data in various ways, interpreting the data, reviewing findings against their predictions and discussing how useful the ideas are.

Not all ideas embodied in the goals of science education can be investigated by first-hand manipulation of objects. Other types of inquiry such as observational and correlational studies often need to be used, for example in relation to the solar system and the interior of the human body. The important point is not so much the physical manipulation but the mental activity, that students are thoughtful participants in obtaining and using evidence and in discussing it with each other.

The important point is not the physical manipulation but the mental activity, that students are thoughtful participants in obtaining and using evidence and discussing it with each other

As well as developing scientific ideas, participation in forms of inquiry provides the experience for students to develop understanding about science and how scientists go about their work. Teaching should therefore

provide opportunities for students to reflect on their participation in science inquiries, how they sought and used evidence and the role of discussion with others in developing their understanding. Understanding the nature, power and limitations of scientific endeavour is also helped by learning about the work of scientists past and present: how scientists raised and answered their questions, what led them to pose those questions, what discussions ensued, and how differences in points of view were resolved or not resolved.

Teacher education courses, pre- and in-service, should recognise that teachers as learners also need to experience scientific activity and discourse at their own level. Courses should include conducting different kinds of scientific inquiry followed by reflection on the conditions and the role of the teacher that supports understanding both in science and about science.

9 Assessment has a key role in science education. The formative assessment of students' learning and the summative assessment of their progress must apply to all goals.

Assessment used as an integral part of teaching to help students' learning is described as formative. Its rationale is that for students to learn with understanding they need to begin from the ideas and skills they already have. The teacher's role is to facilitate this learning by ensuring that activities provide the right amount of challenge to develop ideas and skills. This means finding where the learners have reached in their development and knowing how to move them forward. An important part of this process is helping students to recognise the goals of an activity and how to judge the extent of their achievement of the goals so that students can take a role in directing their effort. Using assessment in this way is on-going, not something that happens after learning, as in the case of summative assessment, and therefore should be built into the programmes and guides that teachers use. Clearly, formative assessment must relate to all goals if teachers are to ensure the best chance of achieving them all.

Using assessment to help learning is on-going, not something that happens after learning, and should be built into teaching programmes and guides

Summative assessment serves a different purpose from formative assessment. It is used to summarise where learners have reached at a particular time in order to report this, for instance, to parents and carers, new teachers at points of transition and transfer, and to the students themselves. As a summary, this information has to be less detailed than is required for formative purposes. It can be derived from the information that has been collected and used to help learning if this information is reviewed against descriptions of achievement at different levels. It can also be arrived at by checking on what students can do at a certain time, by giving tests or special tasks. But in this case it is difficult to ensure that all

goals are assessed by what is necessarily a limited set of test items or special tasks, whereas teachers can summarise information gathered from a wide range of activities and is more completely related to the learning goals. A combination of teachers' assessment and special tasks, where the tasks are used to moderate teachers' judgments, is likely to provide data with the necessary combination of validity and reliability.

What is assessed and reported is assumed to reflect what it is important to learn, so it is essential that this is not limited to what is more readily tested.

10 In working towards these goals, schools' science programmes should promote cooperation among teachers and engagement of the community including the involvement of scientists.

In all areas of learning, schools benefit from communicating to parents and others in the community their goals and ways of working towards them. School life is but a part of children's experience and their out-of-school hours can be used to support their in-school work if the wider community understands what the school aims to do. This is particularly important for science education where the purpose is to understand the world around and opportunities are, therefore, virtually unlimited. The value of sharing the school's vision and goals can go beyond benefiting the students. Many schools create opportunities for parents and others to have the same kinds of experiences of science inquiry as students and so develop their own understanding – for instance of such science-based issues as energy conservation, materials recycling and protection of natural habitats.

The experiences of students in school can also benefit from programmes that actively encourage teachers to work together and with the local community. Science is complex and changing and teaching it is demanding. Few school teachers feel fully confident in all areas of science which they have to teach; indeed, many primary teachers feel confident in rather few areas of science and some secondary school teachers are required to teach all science subjects although they may have only studied one or two in depth. All can benefit from programmes which make provision for teachers to share their expertise with each other in various ways, to have access to advice from scientists, and ideas about the applications of science from those in local industries or engaged in science-based activities in the community. Enabling science students in higher education or research scientists to provide on-line help or visit schools to work directly with students to supplement their learning and help teachers with their subject knowledge allows the science community to contribute to the improvement of science education.

All can benefit from programmes which make provision for teachers to share expertise with each other, to have access to advice from scientists, and ideas about the applications of science from those in local industries or engaged in science-based activities in the community

Section Two
Selecting big ideas in science

Here we discuss answers to some questions that framed our selection of big ideas and identification of progress towards them. The main questions are:

- Should we be concerned with big ideas of science or big ideas of science education – or are they the same?
- How 'big' should big ideas be?
- What criteria should guide the selection?
- Should we confine the ideas to those *resulting from* scientific activity – ideas about the natural world – or include ideas *about* scientific activity and about the use of scientific ideas?

A question not included here relates to the learners for whom these ideas are intended. This is because our principal aim from the start has been to consider big ideas that should be among the aims of science education to be achieved by *all* students by the end of the compulsory years of schooling. Whether or not students proceed to further studies in science, these ideas are ones they need in order to make sense of what they observe in the natural world and to take part in science-based decisions that affect their own and others' wellbeing.

Are ideas of science and of science education the same?

The concern just expressed to equip people with the ideas they need for dealing effectively with science-based questions and decisions in their daily lives positions the discussion firmly in the field of science *education*. Yet it leaves open the questions of whether the big ideas conveyed through studying the natural world in school should be the same as those created through the activity of scientists.

Up to a point it is obvious that they should be the same. Otherwise a disastrous gap would open up between 'school science' and 'real science', a gap of the kind that was so evident in the West during and immediately after the Second World War. But what about the advances made by scientists working at the frontiers of knowledge in almost every domain of science – for instance using the Large Hadron Collider to explore conditions at the time of the 'Big Bang' or decoding the genomes of organisms – which depend on complex knowledge surely far beyond school students? These investigations may well lead to new ideas about the origin of the Universe and what determines the differences among organisms. But although the route to creating and testing new ideas may involve some extremely

complex technologies to collect relevant data, the underlying ideas are not necessarily too complex for school students. As often happens, once identified, ideas can seem very obvious. Thomas Huxley, on reading *The Origin of Species* is reputed to have said 'How stupid of me not to have thought of that'. Even phenomena studied in the Large Hadron Collider and genomics are understandable at some level by someone who has understood that 'all material is made of very small particles' and that 'the cells of all organisms contain genetic material which helps determine their characteristics'. This argument leads to the conclusion that big ideas taught in science education should reflect big ideas in science, expressed in ways appropriate to learners at various stages in cognitive development.

The big ideas taught in science education should reflect big ideas in science, expressed in ways appropriate to learners at various stages in cognitive development

A curriculum expressed in terms of these big ideas should endure beyond the 10- to 15- year life of many national curricula. Certainly, the ways in which fundamental ideas of science are exemplified and studied will change as scientific knowledge advances and informs the content through which ideas are developed. But the goals of learning, set out in the curriculum in terms of big ideas, have a far greater lifetime than the topics through which they are studied at a particular time.

How big are big ideas?

We define big ideas as ideas that can be used to explain and make predictions about a range of related phenomena in the natural world. However, ideas come in different sizes; there are moderately big ideas that can be linked into bigger ideas and some of these can be subsumed into even bigger, more encompassing ideas.

Small ideas are readily identified as falling within the divisions of the familiar domains of different science disciplines. When infants begin to form ideas, these are clearly related to very specific events in their limited world. But they very soon begin to identify patterns in the objects and events they observe; patterns which reflect what we recognise as different domains of science. Thus they distinguish in the first years of life between animate and inanimate objects; they have expectations about the paths of moving objects; and they recognise the difference between some substances. These same patterns are found in children's understanding in the many countries where studies of infants have been carried out and seem to be the roots of the ideas that fall into biology, physics and chemistry. Thus it is not surprising that the big ideas that we have identified tend to fall into these domains of science. However, expressing goals in domain-related terms does not mean that learning has to be within content domains or requires domain-related topics. This would, indeed, conflict with the other Principles in Section 1.

Yet there are also over-arching concepts that cut across domains of scientific ideas. These are at a very high level of abstraction and there are fewer of them. They fall into two kinds – ideas about the world around (such as scale, symmetry, causality, form and function) and ideas about the way in which scientific ideas are generated through human activity.

Among the first kind are ideas that may be reached only when domain-based ideas are secure. They include, for instance, the concept of systems, as being sets of interconnected parts comprising larger entities, which can be usefully studied as a whole. There are such systems within organisms, within machines, within communities and within galaxies. Often there are events in a system where some property or quantity is conserved, such as mass, charge, energy, angular momentum, genes in cell division. Another over-arching idea is that the behaviour of objects and systems shows some regularity that enables relationships to be studied and used to make predictions about likely outcomes of a process. At the same time it is never possible to be completely sure of an observation or measurement; there remains some uncertainty about outcomes, although some are more likely than others.

The second kind of over-arching idea concerns how scientific concepts are created and changed. They include ideas about the nature of evidence, the different types and levels of explanation and the strengths and limitations of ways of modelling complex systems.

Having considered alternatives, we conclude that, for the individual learner who may or may not be embarking on a science-based career, it is the rather less general ideas within content domains that seem most useful. It is the big ideas at this level that science education should aim to help all learners to develop, keeping in mind the point made in relation to Principle 5 about the important difference between curriculum goals and learning experiences. Further breakdown into a range of narrower ideas is, of course, possible but risks losing the connections between the smaller ideas that enable them to merge into a coherent big idea. Expressing the meaning of the big ideas in narrative form, rather than a list of isolated points, is a further attempt to preserve their wholeness.

What criteria should be used in selecting big ideas?

It is not only the ‘size’ of the ideas that has to be considered. What makes the identification of big ideas so difficult is that it depends on judgments as to their relevance and importance in the general education of the whole population. We cannot pack the whole of the sciences into the curriculum goals, so it is necessary to consider what can be left out. Might it be, for instance, that the examples just mentioned – the Large Hadron Collider and genomics – are not considered to be priorities in this context? Many

attempts to identify lists begin with the intention of including only a small number of ideas and end with what is little more than a shuffling of familiar content. It is so difficult to say that certain facts and ideas are *not* needed. This is why we do not think it helpful to identify detailed content to be learned but rather to keep to the ideas that:

*It is difficult to say that certain facts and ideas are **not** needed*

- apply universally
- can be developed through a variety of content, chosen to be relevant, interesting and motivating
- can be applied to new content and enable learners to understand situations and events, as yet unknown, that may be encountered in their lives.

This places emphasis on the processes of learning and of applying knowledge so that the powerful tools that big ideas provide are effectively used in interpreting and understanding the changing world.

Such considerations influence the criteria for selecting big ideas. Combining various suggestions that have been put forward, led to the conclusion that big ideas should:

- have explanatory power in relation to a large number of objects, events and phenomena that are encountered by students in their lives during and after their school years
- provide a basis for understanding issues involved in making decisions that affect their own and others' health and wellbeing, the environment and their use of energy
- provide enjoyment and satisfaction in being able to answer or find answers to the kinds of questions that people ask about themselves and the natural world
- have cultural significance – for instance in affecting views of the human condition – reflecting achievements in the history of science, the inspiration from the study of nature and the impacts of human activity on the environment.

Together these criteria suggest that the ideas are selected not purely to serve an instrumental purpose but to contribute to the satisfaction of understanding the nature of scientific activity and what has been revealed through it. This leads to the question of the inclusion of ideas *about* science and how science is used as well as ideas *of* science.

Should big ideas include ideas about science and about how it is used?

The question of whether to confine discussion to big ideas *of* science – those theories, principles and models that explain phenomena in the

In a world dependent on the applications of science, young people may feel powerless without some understanding not just of how things can be explained but of how to evaluate the quality of the information on which the explanations are based

natural world – or to include big ideas *about* the processes of arriving at these theories, principles and models reflects the philosophical debate about the nature of science. To a certain extent we have sidestepped this by affirming our view that science is multifaceted, encompassing knowledge about the world and the processes of finding that knowledge. In science education these aspects fit together, for what we want learners to understand includes the processes of scientific activity as well as the ideas to which it has led. Indeed, it is hard to envisage separating the two in science education since, without knowing how ideas were developed, learning science would require blind acceptance of many ideas about the natural world that run counter to common sense.

On the other hand, epistemologically the relationship between the content and the processes of science is less obvious. The basis of evidence for content ideas about the natural world is found in the behaviour of entities and organisms in the world, whereas the basis of evidence for ideas about the processes of science is the activity of people, of scientists in arriving at these content ideas. Neither kind of idea is arrived at in a manner free from human judgement but ideas about processes are more easily challenged on this score.

However, the reasons for wanting to define scientific big ideas provide strong arguments for including ideas about scientific activity. In a world increasingly dependent on the applications of science, young people may feel powerless without some understanding not just of how things can be explained but of how to evaluate the quality of the information on which explanations are based. In science this evaluation depends on the methods used in collecting, analysing and interpreting data. Questioning the basis of ideas enables all of us to reject claims that are based on false evidence and to recognise when evidence is being used selectively to support particular actions. This is a key part of using scientific knowledge to evaluate evidence in order to make decisions such as about the use of natural resources. These capabilities are frequently described as constituting ‘scientific literacy’. However, the compass of this phrase has been extended so far that its meaning has become uncertain, and for this reason we have not used it in this discussion.

Summary of the selected big ideas

The discussion of these issues has led us to the selection of the following list of ideas that ought to be reached at the end of compulsory schooling. The brief notes here are not intended to be full summaries but merely to indicate the compass of each. In Section 3 we express the ideas in a narrative form that is more appropriate to indicating progression.

Ideas *of* science

1 All material in the Universe is made of very small particles

Atoms are the building blocks of all materials, living and non-living. The behaviour of the atoms explains the properties of different materials. Chemical reactions involve rearrangement of atoms in substances to form new substances. Each atom has a nucleus containing neutrons and protons, surrounded by electrons. The opposite electric charges of protons and electrons attract each other, keeping atoms together and accounting for the formation of some compounds.

2 Objects can affect other objects at a distance

Some objects have an effect on other objects at a distance. In some cases, such as sound and light, the effect is through radiation which travels out from the source to the receiver. In other cases action at a distance is explained in terms of the existence of a field of force between objects, such as a magnetic field or the universal gravitational field.

3 Changing the movement of an object requires a net force to be acting on it

Objects change their velocity of motion only if there is a net force acting on them. Gravity is a universal force of attraction between all objects however large or small, keeping the planets in orbit round the Sun and causing terrestrial objects to fall towards the centre of the Earth.

4 The total amount of energy in the Universe is always the same but energy can transformed when things change or are made to happen

Many processes or events involve changes and require energy to make them happen. Energy can be transferred from one body to another in various ways. In these processes some energy is changed to a form that is less easy to use. Energy cannot be created or destroyed. Energy obtained from fossil fuels is no longer available in a convenient form for use.

5 The composition of the Earth and its atmosphere and the processes occurring within them shape the Earth's surface and its climate

At the Earth's surface, radiation from the Sun heats the surface and causes convection currents in the air and oceans, creating climates. Below the surface heat from the Earth's interior causes movements in the molten

rock. The solid surface is constantly changing through the formation and weathering of rock.

6 Our solar system is a very small part of one of millions of galaxies in the Universe

Our Sun and eight planets and other smaller objects orbiting it comprise the solar system. Day and night and the seasons are explained by the orientation and rotation of the Earth as it moves round the Sun. The solar system is part of a galaxy of stars, one of many millions in the Universe, enormous distances apart, many of the stars having planets.

7 Organisms are organised on a cellular basis

All organisms are constituted of one or more cells. Multi-cellular organisms have cells that are differentiated according to their function. All the basic functions of life are the result of what happens inside the cells which make up an organism. Growth is the result of multiple cell divisions.

8 Organisms require a supply of energy and materials for which they are often dependent on or in competition with other organisms

Food provides materials and energy for organisms to carry out the basic functions of life and to grow. Some plants and bacteria are able to use energy from the Sun to generate complex food molecules. Animals obtain energy by breaking down complex food molecules and are ultimately dependent on green plants for energy. In any ecosystem there is competition among species for the energy and materials they need to live and reproduce.

9 Genetic information is passed down from one generation of organisms to another

Genetic information in a cell is held in the chemical DNA in the form of a four letter code. Genes determine the development and structure of organisms. In asexual reproduction all the genes in the offspring come from one parent. In sexual reproduction half of the genes come from each parent.

10 The diversity of organisms, living and extinct, is the result of evolution

All life today is directly descended from a universal common ancestor that was a simple one-celled organism. Over countless generations changes resulted from natural diversity within a species which makes possible the selection of those individuals best suited to survive under certain

conditions. Organisms not able to respond sufficiently to changes in their environment become extinct.

Ideas *about* science

11 Science assumes that for every effect there is one or more causes

Science is a search to explain and understand phenomena in the natural world in terms of causes. Proposed explanations should be based on supporting evidence from observations and experiments. There is no single scientific method for generating and testing scientific explanations.

12 Scientific explanations, theories and models are those that best fit the facts known at a particular time

A scientific theory or model representing relationships between variables or components of a system must fit the observations available at the time and lead to predictions that can be tested. Any theory or model is provisional and subject to revision in the light of new data even though it may have led to predictions in accord with data in the past. Every model has its strengths and limitations in accounting for observations.

13 The knowledge produced by science is used in some technologies to create products to serve human ends

The use of scientific ideas in technologies has made considerable changes in many aspects of human activity. Advances in technologies enable further scientific activity; in turn this increases understanding helping to satisfy human curiosity about the natural world. In some areas of human activity technology is ahead of scientific ideas, but in others scientific ideas precede technology.

14 Applications of science often have ethical, social, economic and political implications

The use of scientific knowledge in technologies makes many innovations possible. Whether or not particular applications of science are desirable is a matter that science alone cannot address. Ethical and moral judgments may be needed, based on such considerations as human safety and impacts on people and the environment.

Section Three

From small to big ideas in science

Clearly the big ideas we have identified are complex and mostly involve abstractions that are far beyond the grasp of young children. They cannot be taught in this form; any attempt to do so could only produce rote learning of words which have little meaning in relation to events in the natural world. So we must ask, by what routes do children develop these big ideas of and about science, starting from their early explorations of objects and events around them?

Children's early ideas about the world around

One of the findings from studying babies soon after birth, by observing how they move their heads and their eyes, is that they look particularly at straight lines and contrasts – they like stripes and corners – and their eyes will trace round the outline of objects shown to them, apparently distinguishing objects from their surroundings. They are also fascinated by movement and, by following the movement of objects they see around them, soon become able to predict where a particular moving object will be even though part of its path is obscured; if a rolling ball passes behind a screen they look at the point where it ought to appear again. Using these methods, researchers have inferred that in the first year of life infants understand that inanimate objects cannot move themselves, whereas animate objects can.

Two ideas are particularly important in understanding the world around: the permanence of objects and causality. The idea that objects which seem to disappear must still exist somewhere takes time to develop. If the ball does not appear from behind the screen, the very young baby shows puzzlement but seems not to consider that it is still there. Causality is inferred from observation that some effect invariably follows some action. Infants very soon find that they can cause something to happen and by their first birthday seem to distinguish between psychological causality (for example, getting a response from a parent by smiling or crying) and physical causality (things let go fall downwards). Indeed, as noted in Section 2, young children seem to react to events and phenomena in ways that reflect differences between domains, between movements, living things, different substances.

There is a huge amount of research into children's ideas which show that by the time they enter school they have already formed ideas about many aspects of the world, including scientific ones. Since these are ideas that children have worked out for themselves, and so make sense to them, they

are not to be easily changed, particularly by 'scientific' ideas which are often counter-intuitive (such as that moving objects will continue to move unless there is a force acting on them, rather than stopping by themselves.) Children's ideas have to be taken as the starting point for progress towards more scientific ideas that fit their expanding range of experience.

Models of progression

How children are helped to make these changes depends on how the process of developing ideas is viewed. Consider, for example, three different ways of envisaging progression:

- One way is to identify progression as a **process of climbing a ladder**. Each step has to be completed before the next step can be taken. This is an attractive analogy which is sometimes taken as the basis for creating a set of carefully devised learning activities that follow each other in invariable sequence. There is an assumption that the logic determining the sequence of steps fits how children make sense of experience. The 'ladders' which have been proposed (for instance, the American Association for the Advancement of Science (AAAS) Atlas of Science Literacy Volumes 1 and 2) do take into account what is known about the way children learn but have to make the assumption that this is the same for all, that all learners will feel comfortable climbing the same ladder. Also, as we suggested in discussing Principle 5, the reasons for climbing each rung may not be apparent to the learner, who does not reach 'enlightenment' until getting to the top of the ladder.

- An alternative view is to consider progress as lateral rather than vertical, with larger ideas gradually spreading out from smaller ones, not necessarily in a step-wise progression. Part of the process can be thought of as **completing a jigsaw puzzle**. Although pieces can be assembled in any sequence, it helps to start by fitting a few related pieces together to form larger sections that can be more easily recognised as parts of the whole. Patterns created make it easier to see which further pieces are likely to fit, making the sections bigger. Not everyone works in this way, however; some jigsaw solvers prefer to sort pieces and put together ones that have straight sides and so start from the edges. This analogy draws attention to the fact that it is much easier to solve the problem (and to learn) when there is a picture of the completed puzzle (the big idea) to look at as guidance, compared with not knowing what the pieces can make when put together. The analogy breaks down, however, when we consider that children are all the time encountering new experience, both from formal education and everyday life, and this has to be incorporated into their growing picture of how things work, so the number of pieces changes as time goes on.

But the processes of pattern finding and linking related pieces together remain germane.

- Another model suggested is a 'training' model, in which learning is likened to **training for a marathon**. The capacity for 'going the distance' is built up gradually by running short distances at first, then gradually longer ones. The 'spiral curriculum' is rather like this, where ideas in certain domains are revisited at intervals and hopefully become more powerful each time. Ideally it enables the decision about how far to go in each training session (topic relating to a developing idea) to be based on what was achieved before, but in practice each round is predetermined, thus incurring the same defects as the ladder model.

Something of each of these models is probably needed, because the ways of addressing children's own ideas and moving from smaller to bigger ones vary according to the nature of the idea and the experiences which lead to it. For instance, in some cases children have different ideas about the same phenomenon encountered in different contexts and need some help in linking them and seeing that the more scientific idea applies to both (jigsaw). Often their ideas are based on limited experience and this has to be extended in order to lead to more a widely applicable idea (training). Again, children's reasoning is likely to be limited so that they take notice only of evidence confirming their idea or they retain an idea, despite contrary evidence, for lack of an alternative that makes sense, and which needs to be introduced (ladder).

When trying to make sense of new experience, whether within the classroom or outside, learners start from the ideas they already have; so do scientists when they are trying to explain phenomena and develop their understanding. Ideas 'grow' by being linked to a new experience and tested to see if they help to make sense of the new experience. If a potentially useful idea leads to a prediction that fits the evidence from the new experience, then the idea becomes just a little 'bigger' because it then explains a wider range of phenomena. Even if it doesn't 'work' – and an alternative idea has to be tried – the experience has helped to refine the idea. Through these processes there is a change not only in the number of ideas and events that can be understood, but also a qualitative change in the ideas. Scientific ideas that are widely applicable are necessarily context-independent; for instance, an idea of what makes things float that can be used for all objects and all fluids. To move from an idea of why a particular object floats in water to the big idea of floating is a large step which involves seeing patterns in what happens in very different situations.

When trying to make sense of new experience, learners start from the ideas they already have; so do scientists when they are trying to explain phenomena and develop their understanding

Looking at progress in ideas as a gradual extension from ideas about particular events or objects to those that are powerful in explaining a wide range of experiences has clear implications for pedagogy. We return to

these implications in Section 4, stopping at this point only to note that we are not supposing that learners arrive at their ideas individually and independently, but rather through a process of inquiry and interaction and sharing with others.

Progression towards big ideas in science

For each of the big ideas briefly identified in the last section, the aim here is to set out the small, beginning ideas, followed by the bigger ones which can be developed to encompass a wider range of experiences, leading to the broad, more abstract ideas that enable understanding of objects, phenomena and relationships in the natural world. We attempt the same kind of description of how these understandings are achieved, that is, ideas about science.

At the level of generalisation at which we have chosen to identify big ideas, following the discussion on page 17, some small ideas inevitably contribute to several big ideas. For example, ideas about gravity are needed in the formation of bigger ideas about forces at a distance, about the effect of forces and the solar system. Similarly the impact of human activity on organisms and the environment is part of the story of competition among species, diversity of organisms and the applications of science.

Under each heading we begin with the small and contextualised ideas that children in the primary school, through appropriate activities and with support, will be able to grasp. These are followed by ideas that lower secondary school students can develop as their increasing capacity for abstract thinking enables them to see connection between events or observations (for instance, that certain changes can be explained in terms of energy transfer, or that properties of materials can be explained by considering matter to be made of particles). As exploration of the natural world extends in later secondary education, continuation of this creation of patterns and links enables students to understand relationships and models that can be used in making sense of a wide range of new and previous experiences.

In describing these progressions we have not attempted to set boundaries between what can be learned in years 1-3, 4-6, etc. We are not convinced that it is possible, or necessarily useful, to identify definite boundaries given a certain diversity in the paths of cognitive development of individual children. Rather, what it important is the general direction of progress towards useful explanatory frameworks. How far children can move in this direction at any time depends on a number of contextual variables, not least the pedagogy they experience, as discussed in the next section.

1 All material in the Universe is made of very small particles

All the 'stuff' encountered in everyday life, including air, water and different kinds of solid substances, is called material because it has mass and takes up space. Different materials are recognisable by their properties, some of which are used to classify them as solids, liquids or gases.

When some materials are combined they form a new material with different properties than the original materials; other materials simply mix without changing permanently and can be separated again. Materials can also be changed by heating or cooling. The amount of material does not change when a solid melts or a liquid evaporates.

If a material could be divided into smaller and smaller pieces it would be found to be made of pieces, particles, smaller than can be seen even with a microscope. These particles are not *in* a material; they *are* the material. All the particles in a particular material are the same and different from those in other materials. The particles are not static but move in random directions. The speed at which they move is experienced as the temperature of the material. The particles can attract or repel each other. The differences between solids, liquids and gases can be explained in terms of the movement of particles and the separation and strength of the attraction between neighbouring particles. The stronger the force of attraction between the particles the more energy is needed to separate them, for example in going from a solid to a liquid form or from a liquid to a gas. This is why materials have different melting and boiling points.

The smallest piece of a material is called an atom. All materials, anywhere in the universe, living and non-living, are made of a very large numbers of these basic 'building blocks' of which there are about 100 different kinds. Substances made of only one kind of atom are called elements. Atoms of different elements can be combined together to form a very large number of compounds. A chemical reaction involves a rearrangement of the atoms in the reacting substances to form new substances, while the total amount of matter remains the same. The properties of different materials can be explained in terms of the behaviour of the atoms and groups of atoms of which they are made.

Atoms themselves have an internal structure, consisting of a nucleus, made of protons and neutrons, surrounded by electrons. The electrons and protons have electric charge – that of an electron being called negative and that of a proton called positive. Atoms are neutral, charges balancing exactly. Electrons move rapidly in matter, forming electric currents and causing magnetic forces. Their net effect is a force of attraction holding atoms and molecules together in compounds. When some electrons are removed or added, the atoms are left with a positive or negative charge and are called ions.

In some atoms the nucleus is unstable and may emit a particle, a process called radioactivity. This process involves the release of radiation and an amount of energy far greater than any reaction between atoms.

2 Objects can affect other objects at a distance

Objects can have an effect on other objects even when they are not in contact with them. For instance, light is seen both from sources such as light bulbs or flames close by and from the Sun and stars very long distances away. This is because these objects give out light, which travels from them in various directions and is detected when it reaches and enters our eyes. Things that are seen either give out or reflect light that human eyes can detect. Sound comes from things that vibrate and can be detected at a distance from the source because the air or other material around is made to vibrate. Sounds are heard when the vibrations in the air reach our ears.

Other examples of objects affecting other objects without touching them are the force of gravity that makes things falls to the Earth, the forces between magnets or electric charges. When things that are unsupported fall downwards they are being pulled by the attraction of the Earth, which holds all things on the Earth. Magnets can pull things made of iron and attract or repel other magnets without touching them. There is also attraction and repulsion between objects that are electrically charged.

Visible light is one example of radiation, which spreads out in a way resembling how waves spread across water. Other kinds of light are not visible to the human eye and include radio waves, microwaves, infra-red, ultra-violet, X rays and gamma radiation, which differ from each other in wavelength. These can all travel through empty space. Thinking of radiation as waves can help to explain how it behaves. Although sound spreads out like waves it cannot travel through empty space; there has to be some continuous material between the sources and the receiver for the vibrations to travel through.

When radiation hits another object, it may be reflected by it, absorbed or scattered by it, pass through it, or a combination of these. When reflected by a mirror or transmitted through a transparent material, the radiation remains the same, but when it is absorbed in an object it changes and usually causes a rise in temperature of the object.

Some cases of action at a distance are not explained in terms of radiation from a source to a receiver. A magnet, for example, can attract or repel another magnet and both play equal parts. Similarly, the attraction and repulsion between electric charges is reciprocal. The pull downwards that makes an object fall when released is also the result of attraction at a distance – between the object and the Earth. There is a gravitational force between all objects, which depends on their mass and distance apart. It is only felt when one or more of the objects has a very large mass, as in the case of the Earth pulling things towards it. The idea of a field is useful for thinking about such situations. A field is the region of the object's influence around it, the strength of the field decreasing with distance from the object. Another object entering this field experiences an effect – an attraction or a repulsion.

3 Changing the movement of an object requires a net force to be acting on it

Forces can push, pull or twist objects, making them change their shape or motion. Things only change their motion if there is a net force acting on them.

How quickly an object's motion is changed depends on the force acting and the object's mass. The greater the mass of an object, the longer it takes to speed it up or slow it down, a property of mass described as inertia.

Gravity is a universal force of attraction between all objects however large or small which results in everything on the Earth being pulled down towards the centre of the Earth. We identify this downward force as the weight of the object. The object pulls the Earth as much as the Earth pulls the object, but the Earth's mass being much bigger, we observe the resulting motion of the object, not of the Earth. The downward force of gravity on an object on the Moon is less than that on Earth because the Moon has less mass than the Earth, so a person on the Moon appears to weigh less than on Earth even though their mass is the same. The pull of the Earth on the Moon keeps it orbiting the Earth while the pull of the Moon on Earth gives rise to tides.

An object which stays at rest on the surface of the Earth has one or more forces acting on it counter balancing the force of gravity. A book lying on a table does not fall because the atoms in the table are pushing upwards on the object with a force equal to the downward force of gravity.

When forces acting on an object are not equal and opposite in direction, their resulting effect is to change the object's motion, to speed it up or slow it down. Conversely an object's motion does not change unless there is a net force acting on it. Often the force that is acting is not recognised as a force and a moving object, such as a rolling ball, is assumed to slow down automatically. In fact its motion is gradually being slowed by the force of friction. In all cases change in motion is caused by unbalanced forces. If no net force is acting any motion will not change; the object will remain stationary or, if in motion, go on forever in a straight line, as do stars in the sky. Change in motion is in the direction of the net force; motion at right angles is not affected. Satellites stay in orbit round the Earth because they are sent off with enough force to reach a height where their motion is in a curved orbit around the Earth due to the force of gravity constantly changing the direction of motion and there is no air resistance to slow them down.

When opposing forces acting on a solid object are not in the same line, they act to turn or twist the object. The effect of a turning force depends on its distance from the axis about which it turns. This has many applications in tools and machines.

Pressure is a measure of the amount of force acting on a particular area. A force spread over a larger area produces less pressure than when spread over a smaller area, a relationship with many applications, from snow shoes to drawing pins.

4 The total amount of energy in the Universe is always the same but energy can be transformed when things change or are made to happen

There are various ways in which things can be made to happen or change. Things can be made to change their movement by pushing or pulling. Heating things can make them change, as in cooking, melting solids or changing water to vapour. Electricity can make light bulbs glow.

In all these cases, what is needed to make things change is called energy and in the process of change energy is transformed from one form to another. An object which transfers energy to something else is called a source of energy, although it does not create energy but must obtain it from itself or somewhere else.

Objects have energy either because of their chemical composition (as in fuels and batteries), their movement, their temperature, their position in a gravitational or other field, or because of compression or distortion of an elastic material. Energy can be stored by lifting an object higher above the ground so that when it is released and falls this stored energy can make something change. When an object is heated it has more energy than when it is cold. Heat moves from an object at a higher temperature in contact with one at a lower temperature until both objects are at the same temperature. How quickly this happens depends on the kind of material through which the heat flows. The chemicals in the cells of a battery store energy which is released when the battery is connected so that an electric current, carrying energy, flows. Energy can be transported by radiation, as sound in air or light in air or a vacuum.

Many processes and phenomena are explained in terms of energy exchanges, from the growth of plants to the weather. The transfer of energy in making things happen almost always results in some unwanted thermal energy being produced and spread out by conduction or radiation. Thermal energy is the random movement of atoms and molecules and energy in this form cannot as easily be used.

Energy cannot be created or destroyed. When energy is transferred from one object to others the total amount of energy in the universe remains the same; the amount that one object loses is the same as the other objects gain. When the Sun heats the Earth, the Sun is gradually losing energy through radiation. The mass of atoms is a form of stored energy, called nuclear energy. Radioactive atoms may release this energy and make it available as heat.

Across the world, the demand for energy increases as human populations grow and because modern lifestyles require more energy, particularly in the convenient form of electrical energy. Since fossil fuels, frequently used in power stations and generators, are a limited resource, other ways of generating electricity have to be sought, whilst reducing demand by improving the efficiency of the processes in which we use it.

5 The composition of the Earth and its atmosphere and the processes occurring within them shape the Earth's surface and its climate

There is air all around the Earth's surface but there is less and less further away from the surface (higher in the sky). Weather is determined by the conditions of the air. The temperature, pressure, direction and speed of movement and the amount of water vapour in the air combine to create the weather. Measuring these properties over time enables patterns to be found that can be used to predict the likelihood of different kinds of weather.

Much of the solid surface of the Earth is covered by soil, which is a mixture of pieces of rock of various sizes and the remains of organisms. Fertile soil also contains air, water, some chemicals from the decay of living things, particularly plants, and various living things such as insects, worms and bacteria. The solid material beneath the soil is rock. There are many different kinds of rock with different composition and properties. The action of wind and water wears down rock gradually into smaller pieces – sand is made of small pieces of rock and mud of still smaller pieces.

The layer of air at the Earth's surface is transparent to most of the radiation coming from the Sun, which passes through. This radiation, absorbed at its surface, is the Earth's external source of energy. Radioactive decay of material inside the Earth since it was formed is its internal source of energy. Radiation from the Sun provides the energy for plants containing chlorophyll to make glucose through the process of photosynthesis. The radiation from the Sun absorbed by the Earth warms the surface which then emits radiation of longer wavelength (infra-red) that does not pass through the atmosphere but is absorbed by it and keeps the Earth warm. This is called the greenhouse effect because it is similar to the way in which the inside of a greenhouse is heated by the Sun.

Oxygen in the atmosphere, produced by plants during photosynthesis, indirectly protects the Earth from the short wave (ultra-violet) part of the Sun's radiation which is harmful to many organisms. The action of ultra-violet radiation on oxygen in the upper atmosphere produces ozone thus absorbing this harmful radiation. Ozone in the atmosphere can be broken down by certain chemicals resulting from human actions on Earth.

Beneath the Earth's solid crust is a hot layer called the mantle. The mantle is solid when under pressure but melts (and is called magma) when the pressure is reduced. In some places there are cracks (or thin regions) in the crust which can allow magma to come to the surface, for example in volcanic eruptions. The Earth's crust consists of a number of solid plates which move relative to each other, carried along by movements of the mantle. Where plates collide, mountain ranges are formed and there is a fault line along the plate boundary where earthquakes are likely to occur and there may also be volcanic activity. The Earth's surface changes slowly over time, with mountains being eroded by weather, and new ones produced when the crust is forced upwards.

6 Our solar system is a very small part of one of millions of galaxies in the Universe

Our Sun is one of many stars that make up the Universe. The Earth moves round the Sun taking about a year for one orbit. The Moon orbits the Earth taking about four weeks to complete an orbit. The Sun, at the centre of the solar system, is the only object in the solar system that is a source of visible light. The Moon reflects light from the Sun and as it moves round the Earth only those parts illuminated by the Sun are seen, which accounts for the changes in how it appears at different times. The Earth rotates about an axis lying north to south and this motion makes it appear that the Sun, Moon and stars are moving round the Earth. This rotation causes day and night as parts of the Earth's surface turn to face towards or away from the Sun.

It takes a year for the Earth to pass round the Sun. The Earth's axis is tilted relative to the plane of its orbit round the Sun so that the length of day varies with position on the Earth's surface and time of the year. The tilt of the Earth's axis gives rise to the seasons.

The Earth is one of eight (so far known) planets in our solar system which, along with many other smaller bodies, orbit the Sun, in roughly circular paths, at different distances from the Sun and taking different times to complete an orbit. The distances between these bodies are huge – Neptune is 4.5 billion km from the Sun, 30 times further than Earth. As seen from Earth, planets move in relation to the positions of the stars.

Occasionally a large chunk of rock orbiting the Sun gets close enough to the Earth to be pulled into its gravitational field and accelerates through the atmosphere where friction between the air and the surface of the rock causes it to heat up and glow, when it can be seen as a 'shooting star'. Otherwise movements of object within the solar system are mostly regular and predictable. The same scientific laws, or generalisations about how things behave, that apply on Earth also apply throughout the Universe. There is evidence from space exploration that changes have taken place on the surface of the planets since they were formed.

The next nearest star is much further away than the distance of the furthest planet, Neptune. Our Sun is one of millions of stars that together make up a galaxy called the Milky Way. There are millions of galaxies in the universe, almost unimaginably vast distances apart – and all are moving rapidly away from each other. This movement of galaxies suggests that the Universe is expanding from a past state called the 'big bang', towards a future which is still unclear.

7 Organisms are organised on a cellular basis

Living things (organisms) are distinguished from non-living things by their ability to move, reproduce and react to certain stimuli. To survive they need water, air, food, a way of getting rid of waste and an environment which stays within a particular range of temperature. All living organisms are made of one or more cells, which can be seen only through a microscope.

All the basic functions of life are the results of what happens inside cells. Cells divide to make more cells in growth and in reproduction and they extract energy from food in order to carry out these and other functions. Some cells in multicellular organisms, as well as carrying out the functions that all cells do, are specialised; for example, muscle, blood and nerve cells which carry out specific functions within the organism. Cells are often aggregated into tissues, tissues into organs, and organs into organ systems. In the human body, systems carry out the key functions of respiration, digestion, elimination of waste and temperature control. The circulatory system takes material needed by cells to all parts of the body and removes soluble waste to the urinary system.

Within cells there are many molecules of different kinds which interact in carrying out the functions of the cell. In multi-cellular organisms cells communicate with each other by passing substances to nearby cells to coordinate activity. A membrane around each cell plays an important part in regulating what can enter or leave a cell. Activity within different types of cell is regulated by enzymes. Hormones, released by specialised tissues and organs, regulate activity in other organs and tissues and affect the overall functioning of the organism. In humans, most hormones are transported in the blood. Disease is often the result of malfunctioning cells; many medicines operate by speeding up or slowing down the regulatory mechanisms of enzymes or hormones. The brain and spinal cord also contribute to the regulation of cell activity, by sending messages along nerve cells in the form of electrical signals, which travel quickly between cells.

Cells function best in certain conditions, particularly of temperature and acidity. Both single cells and multi-cellular organisms have mechanisms to maintain temperature and acidity within certain limits that enable the organism to survive.

8 Organisms require a supply of energy and materials for which they are often dependent on or in competition with other organisms

All living things need energy for food as well as air, water and certain temperature conditions. Plants containing chlorophyll can use sunlight to make the food they need and store food that they do not immediately use. Animals need food that they can break down and which comes either directly by eating plants (herbivores) or by eating animals (carnivores) which have eaten plants or other animals. Animals are ultimately dependent on plants for their survival. The relationships among organisms can be represented as food chains and food webs.

Some animals are dependent on plants in other ways as well as for food, for example shelter and, in the case of human beings, for clothing and fuel. Plants also depend on animals in various ways. For example, flowering plants may depend on insects for pollination and on other animals for dispersing their seeds.

Interdependent organisms living together in particular environmental conditions form an ecosystem. In a stable ecosystem there are producers of food (plants), consumers (animals) and decomposers, which are bacteria and fungi which feed on waste products and dead organisms. The decomposers produce materials that help plants to grow, so the molecules in the organisms are constantly re-used. At the same time, energy passes through the ecosystem. When food is used by organisms for life processes some is dissipated as heat but is replaced in the ecosystem by energy from the Sun being used to produce plant food.

In any given ecosystem there is competition among species for the energy and materials they need to live. The persistence of an ecosystem depends on the continued availability of these materials in the environment. Plant species have adaptations to obtain the water, light, minerals and space they need to grow and reproduce in particular locations characterised by climatic, geological and hydrological conditions. If conditions change, the plant populations may change, resulting in change of animal populations.

9 Genetic information is passed down from one generation of organisms to another

Living things produce offspring of the same kind, but in many cases offspring are not identical with each other or with their parents. Plants and animals, including humans, resemble their parents in many features because information is passed from one generation to the next. Other features, such as skills and behaviour, are not passed on in the same way and have to be learned.

The information that is passed between generations is in the form of a code represented in the way that the parts of a large molecule called DNA are put together. A gene is a length of DNA; and hundreds or thousands of genes are carried on a single chromosome. In the human body most cells contain 23 pairs of chromosomes with a total of about twenty five thousand genes. These provide the information that is needed to make more cells in growth and reproduction.

When a cell divides as in the process of growth and replacement of dead cells, this genetic information is copied so that each new cell carries a replica of the parent cell. Sometime an error occurs in replication, causing a mutation, which may or may not be damaging to the organism. Changes in genes can be caused by environmental conditions, such as radiation and chemicals. These changes can affect the individual but only affect the offspring if they occur in sex (sperm or egg) cells.

In sexual reproduction, a sperm cell from a male unites with an egg cell from a female. Sperm and egg cells are specialised cells each of which has one of the two versions of each gene carried by the parent, selected at random. When a sperm and egg combine half the genetic material in the fertilised egg is from the sperm cell and half from the egg cell. As the fertilised egg divides time and time again this genetic material is duplicated in each new cell. The sorting and recombining of genetic material when egg and sperm cells are formed and then fuse results in an immense variety of possible combinations of genes, and in differences that can be inherited from one generation to another. These provide the potential for natural selection as a result of some variations making organisms better adapted to certain environmental conditions.

Asexual reproduction, which occurs naturally in a wide range of organisms including some bacteria, insects and plants, leads to populations with identical genetic material. Biotechnology has made possible the production of genetically identical organisms through artificial cloning in a range of species including mammals.

More is being learned all the time about genetic information by mapping the genomes of different kinds of organisms. When sequences of genes are known genetic material can be artificially changed to give organisms certain features. In gene therapy special techniques are used to deliver into human cells genes that may one day cure disease.

10 Diversity of organisms, living and extinct, is the result of evolution

There are many different kinds of plants and animals in the world today and many kinds that once lived but are now extinct. We know about these from fossils. Animals and plants are classified into groups and subgroups according to their similarities. For example within the group of animals called birds, there are families of birds such as titmice and, within a family, different kinds (species), such as blue tits, great tits and long-tailed tits. Organisms of the same species breed more of the same. Different species cannot usually interbreed.

Although organisms of the same species are very similar they vary a little from each other. Living things are found in certain environments because they have features that enable them to survive there. This adaptation to their environment has come about because of the small differences that occur during reproduction, resulting in some individuals being better suited to the environment than others. In the competition for materials and energy, those that are better adapted will survive and may pass on their adapted feature to their offspring. Those less suited to a particular environment may die before reproducing, so later generations will contain more of the better adapted individuals. This only occurs if the changes result from mutations (changes) in the reproductive cells. Changes in other cells are not passed on.

The natural selection of organisms with certain features which enable them to survive in particular environmental conditions has been going since the first form of life appeared on Earth about 3.5 billion years ago. Simple single-celled organisms arose early in the history of life. About two billion years ago some of these evolved into multi-cellular organisms that eventually gave rise to today's large animals, plants and fungi. Other forms remained uni-cellular.

When climatic, geological or population changes occur, the benefit of particular inherited features may be enhanced or diminished. Human activity can impose far-reaching effects on the environment and has already resulted in changes that are damaging to many organisms. The present rate of extinction as a result of human activities is literally hundreds of times what is would be if there were no people. Maintaining diversity of species and within species is important. A reduction in the diversity of life can lead to significant ecosystem degradation and loss of ability to respond to changes in the environment.

11 Science assumes that for every effect there is one or more causes

Science is about finding explanations for why things happen as they do or why they take a particular form, assuming that every effect has a cause or causes and that there is a reason for the form things take. An explanation is not a guess, there has to be some reason for it. There are various ways of finding out what makes things work or why they happen. Careful observation, including measurement where possible, can suggest what may be happening. In other cases it is possible to do something to make something change and observe what happens. When this is done it is important, if possible, to see that other things stay the same so that the result can only be the effect of changing one thing.

Any claim about what explains a particular event or condition should be based on evidence to support it. Careful and systematic observations and accurate description of what is observed is fundamental to scientific investigation. It is important to realise that sometimes what people expect to happen influences what they observe, so it is good practice for observations to be made by several people independently.

There can be different ideas about what explains something, so evidence is needed to sort out which idea really 'works'. A possible explanation (hypothesis) indicates the factor or factors that are thought to explain a phenomenon. To test it, the hypothesis is used to predict what will happen when that factor is changed and then observations are made to see if the evidence of what happens fits the prediction. If the result agrees with the prediction, and no other factors produce the same result, then the factor is accepted as the best current explanation of the phenomenon. Often, however, there are several interacting factors and the role of each may be uncertain.

In cases where factors cannot be experimentally manipulated, as in the case of the movement of planets in the solar system, a phenomenon can be investigated by observing systematically on several occasions and over a period of time. Looking for patterns in the data may reveal that there is a correlation between factors – as one factor changes, so does another in a regular way. A correlation may be used to propose an underlying model, which can be used to make predictions, even though it may involve aspects that cannot be directly observed or changed. However, a correlation cannot usually be taken as conclusive evidence that the factor is the cause of the change. Furthermore, finding that one thing is the cause of an effect is not the same as explaining the mechanism by which the effect is brought about. For that, a model of the relationships based on scientific principles is needed.

Phenomena that occurred in the past, such as rock changes or species evolution, can also be submitted to the process of hypothesis testing. In such cases, it is the coherence of all hypotheses consistent with all known facts and scientific principles which provides the best possible explanation.

12 Scientific explanations, theories and models are those that best fit the facts known at a particular time

Everyone can ask questions about things in the natural world and can do something to find answers that help to understand what is happening. Science is doing this through some kind of systematic inquiry that involves collecting data by observing or measuring features of the objects being studied or from other sources. Whether or not a good explanation can be obtained depends on what data are collected and this is usually guided by having some theory or hypothesis about what might be happening.

To help in the process of explaining observations and what makes things happen, scientists create models to represent what they think may be happening. These are sometime physical models, such as a model of the solar system where various objects are used to represent the Sun, Moon, Earth and other planets, or a model of how atoms are thought to be arranged in a compound. Other models are theoretical, such as in representing light as a wave motion, and often represent relationships as mathematical formulae. Some models are firmly established in theories which have been shown to work without contradiction in all contexts so far encountered. Others are more tentative and are likely to be changed in future. Sometimes there is more than one possible model and the evidence of which works best is not conclusive; and in other cases we do not yet have a satisfactory explanatory model.

Creating models of any kind requires the ability to imagine the way things might relate to each other as well as using what is already known. They provide ways of explaining phenomena in terms of relationships between parts of a system. Model-based reasoning means going beyond what can be directly observed, whilst still keeping the link with the evidence by comparing what a model predicts with what can be observed.

Theories and models are tested by being used to make predictions about the effects of certain changes and then seeing if the predictions are confirmed by collecting new data. Once data have been collected they need to be interpreted to try to explain what has been found. Explanations do not emerge self-evidently from data but are created in a process that often involves intuition, imagination and informed hypothesis.

If new data do not fit current ideas then the ideas have to change. Although there is greater confidence in a theory or model that leads to predictions that are then found to agree with observations, an explanation or theory can never be proved ‘correct’ because there is always the possibility of further data conflicting with it. So some scientific ideas used today to explain things around us are different from the ones accepted in the past and some may well be different in the future.

13 The knowledge produced by science is used in technologies to create products to serve human needs

Technology helps to provide people with things they need or can use, such as food, tools, clothes and somewhere to live. Making these things involves selecting the materials that have the best properties for a particular use. Materials that come from plants and animals or from the Earth's surface have been used for thousands of years, whilst manufactured materials, such as plastics, have been produced only since the beginning of the twentieth century. These artificial materials can be made to have properties as required, making new products available.

The application of science in making new materials is an example of how scientific knowledge has helped advances in technology. The application of science in making new tools and machines has also made mass production possible so more people have access to a range of commodities. At the same time technological advances have helped scientific developments by improving instruments for observation and measuring, automating processes that might otherwise be too dangerous or time consuming to undertake, and particularly through the provision of computers. Thus use of technology aids scientific advances which in turn can be used in designing and making things for people to use. In some cases, technological products have been in advance of scientific ideas, whilst in other cases scientific understanding came first.

There are disadvantages as well as advantages to some technological products. Although the use of some artificial materials may mean less demand on scarce natural ones, many new materials do not degrade as do natural materials. They present a waste disposal problem when discarded. Also, some technological devices such as mobile telephones and computers use metals that exist in the Earth only in small quantities and soon could be used up. Such examples reflect a wider problem, namely the need to recycle materials to conserve sources and to reduce pollution. When there are adverse effects on the environment which affect people's lives, scientists and technologists need to collaborate in understanding the problem and in finding solutions.

14 Applications of science often have ethical, social, economic and political implications

The understanding that is developed through science enables us to explain how some things in the natural world work. This understanding can often be applied to change or make things to help solve human problems. Such technological solutions have improved the lives and health of many people in countries across the world in the past two decades. Clean water, adequate food and improved medicines have increased human life expectancy. At the same time the resulting population growth has increased demands on resources and on space on the Earth's surface for increased food production, housing and disposal of waste. This has often been detrimental to those in developing countries and resulted in the destruction of habitats of other living things, causing some to become extinct.

There are many examples of how technological advances have unintended consequences. Improved ease and speed of transport, particularly by air, burns fuel that produces carbon dioxide, one of several gases in the atmosphere that keep the Earth warm through the greenhouse effect. Increase in these gases in the atmosphere raises the Earth's temperature. Even a small increase in temperature of the Earth can have widespread effects through changes in the polar ice, sea levels and weather patterns. In all such cases, if the detrimental effects are known, the trade-off between the advantages and the disadvantages of the application of science needs to be carefully considered.

Science can help in understanding implications of certain applications but decisions about whether they should be undertaken will require ethical and moral judgements which are not provided by science. There is also the use of scarce resources to be considered. All innovations consume resources of some kind including financial resources so decisions have to be made when there are competing demands. These decisions, whether at governmental, local or individual level, should be informed by understanding of the scientific concepts and the technological principles involved.

Section Four
Working with big ideas in mind

The question which we address in this section concerns how learning is to be guided towards the development of big ideas in a manner consistent with the principles underpinning essential education in science. A full answer to this question would need to consider the curriculum, the pedagogy, the knowledge and role of the teacher, the role of the students and the role of learning resources (including materials, natural phenomena and people). Our focus here is pedagogy and so we deal only briefly with the other factors.

It is the role of the written curriculum to set out the goals of learning and the principles that should guide its implementation. Having in mind the overall aim of helping all students develop big ideas has implications for the form in which the goals are set out. The ideas should be expressed in terms that everyone can understand – not just teachers, educational researchers and scientists but also parents and others concerned with students' education. Descriptions, such as in Section 3, perhaps with more detail and explanation, provide a useful way of communicating that the ultimate goal is the understanding of relationships, not a series of facts, or a collection of 'small ideas'. The curriculum document should also set out the progress towards big ideas in a way that makes clear that the process of broadening understanding is on-going and continuous. The aim should be to make it possible for teachers, parents and others to relate the activities of students to some point in the progression towards big ideas, thus making clear the purpose of the activities.

A curriculum based on big ideas may well have universal relevance since science is universal. But cultural and economic circumstances will determine how the curriculum can be implemented in different countries. As we said in Principle 5, it is not the role of the curriculum to set out *how* the goals are to be achieved. Implementation is the role of pedagogy.

Pedagogy

Pedagogy, in its broadest sense, means not only the act of teaching but also the theories, values and justifications that underpin it and the skills and creativity needed to provide effective learning activities and to engage students in them.

In making decisions about these aspects of pedagogy our Principles are a key reference point. The first Principle requires that a general aim for science education is the development of affective responses to

investigating the natural world. This is reinforced by Principle 7 which, whilst not denying that learning science should be 'fun', stimulating wonder about the natural world, states that this should not be the only aim of students' activities; these should also advance students' understanding. No activity can be content-free, but it can be free of science content even though appearing to employ skills used in science. This is underlined also in Principle 2 which affirms the aim that all students acquire the general facility with things scientific that is implicit in the term 'scientific literacy'. This can only happen by students engaging with content that leads to scientific understanding.

No activity can be content-free but it can be free of science content even though appearing to employ skills used in science

Principles 3 and 8 are particularly concerned with the achievement of a range of goals including skills and attitudes as well as big ideas. The importance of skills to the development of ideas follows from earlier (p26) discussion of how students attempt to make sense of new experience, by applying and testing existing ideas, as do scientists. The usefulness of an idea is tested by making a prediction and then collecting new evidence to see if this agrees with the prediction. The result may mean that the idea is found to explain the new experience and so becomes 'bigger' because it encompasses more phenomena. Or the idea may be rejected as not fitting the new evidence and an alternative has to be found. What emerges from this testing, however, depends on how the prediction, observation, collection and interpretation of data are carried out; in other words on the extent to which scientific inquiry skills have been used. Thus inquiry skills have a key role in the development of ideas and helping students to use these skills is an important goal of science education. The pedagogy that supports the development of big ideas must, therefore, also promote the development of inquiry skills.

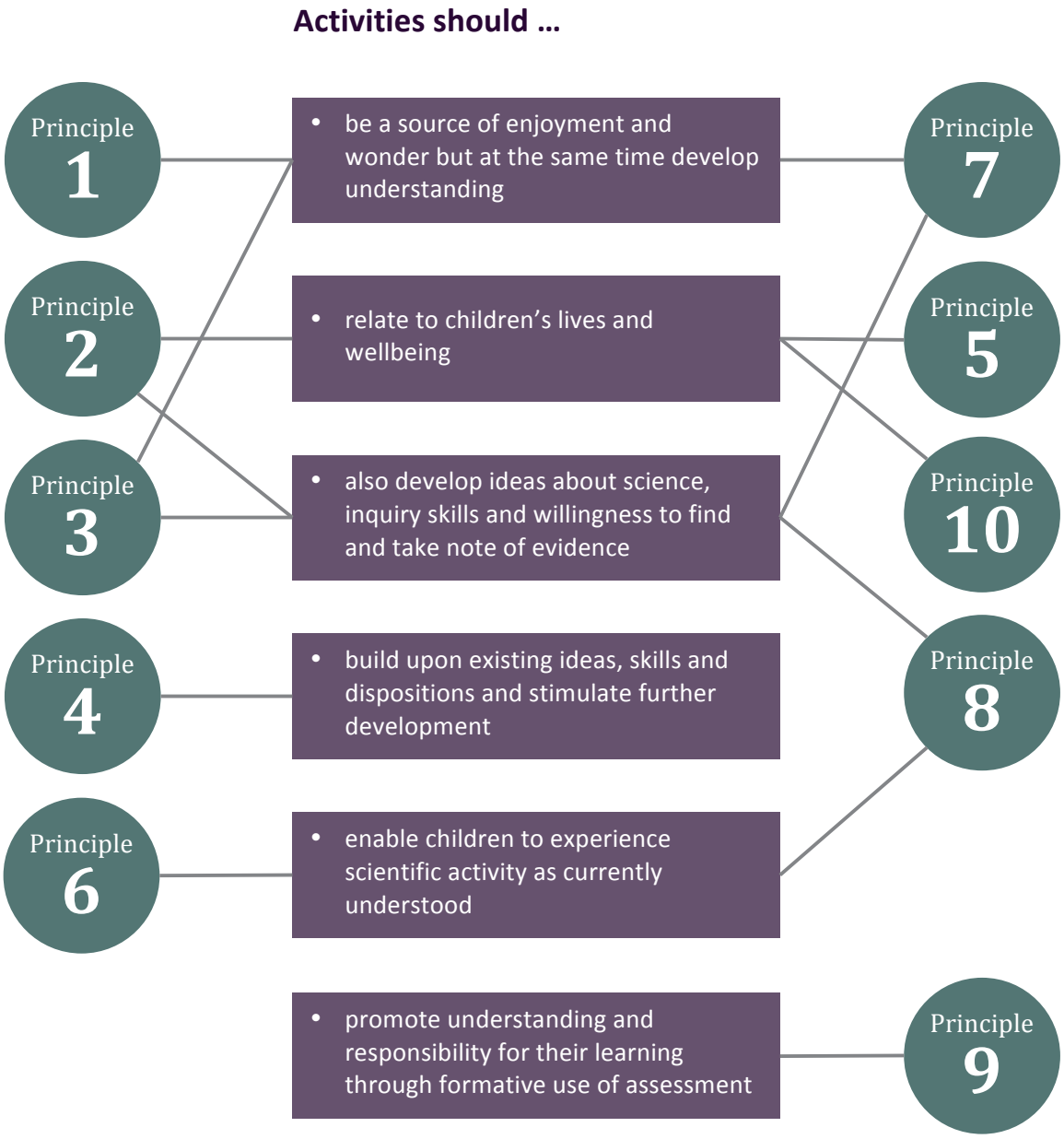
Principles 4 and 5 require that activities are such that students can link them to their everyday experience and previous learning, whilst Principle 6 requires that teachers involve students in developing their emerging ideas through various kinds of scientific activity reflecting the range used by scientists. Principle 9 sets out a role for assessment as part of teaching which helps to regulate the amount of challenge that activities provide and involves students in decisions about how to make progress. It requires teachers and students to be clear about goals and teachers to know where students have reached in developing ideas and skills. Principle 10 refers to the role of human and other resources and the mutual benefit to schools and their communities of collaboration.

The pedagogy that supports the development of big ideas must also promote the development of inquiry skills

Implications both for the content and for pedagogy follow from applying the principles to the selection of students' activities. In relation to the content, spending science learning time inquiring into particular phenomena or events ought to be justified in terms of helping progress towards big ideas. Perhaps this is not in fact a particularly stringent

requirement since the ideas that we have identified are capable of broad interpretation. Nevertheless, the exercise of clarifying the contribution to this development is a useful one, if only to avoid falling into the trap of repeating activities year after year as a matter of habit, or because they always 'work'.

Applying principles to students' activities in science education



But whether or not there is learning related to big ideas is also dependent on the pedagogy – how the students are helped to engage with, think about and link the subject matter to other experiences. Even potentially relevant and engaging content can fail to advance understanding if the activities are reduced to following instructions and learning answers by rote. Such activities fail to contribute to the goals of science education of Principle 3.

Aspects of effective pedagogy in science

Pedagogy that is consistent with the Principles includes the features currently widely endorsed as central to effective practice: inquiry, individual and social constructivism, and the formative use of assessment. These are different but complementary aspects of pedagogy.

Inquiry means that students are developing their understanding through their own investigation, that they are gathering and using data to test ideas and find the ideas that best explain what is found. The source of data may be the direct manipulation of materials, observation of phenomena or use of secondary sources including books, the internet and people. The interpretation of the data to provide evidence to test ideas may involve debate with other students and their teacher and finding out what experts have concluded. Implicit in all of this is that students are taking part in activities similar to those in which scientists engage in developing understanding. By making these activities conscious, students develop their ideas *about* science.

Constructivism refers to the conscious revealing of students' existing ideas, skills and attitudes in relation to an event or phenomenon being studied and the use of this information in helping further learning. It acknowledges that students are the agents in developing or changing their ideas and in practice means helping students to consider alternative ideas that may be more useful than their own in explaining the world around. An important source of alternative ideas is the discussion of others' ideas, so rather than expecting students to develop their ideas individually (individual constructivism) it is more fruitful to encourage discussion and argumentation in which ideas are developed socially. The process of communicating and defending ideas helps students to reformulate their own ideas taking account of those of others.

The formative use of assessment is a continuing cyclical process in which information about students' ideas and skills informs on-going teaching and facilitates active engagement in learning. It involves the collection of evidence about learning as it takes place, the interpretation of that evidence in terms of progress towards the goals of the work, the identification of appropriate next steps and decisions about how to take

Pedagogy consistent with the Principles includes the features currently endorsed as central to effective practice: inquiry, individual and social constructivism, and the formative use of assessment

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them. It has a role in regulating the teaching and learning processes to ensure progression in learning with understanding, by providing feedback to both teacher and student. It is also central to enabling students to acquire ownership of their learning, one of the key features of genuine understanding. Ownership requires that students know the goals of their work and the quality criteria to be applied so that they can themselves assess where they are in relation to the goals. This puts them in a position to identify, with their teachers, the next steps in their learning and to take some responsibility for progress towards the goals.

Whilst these three aspects of pedagogy overlap, they make different contributions to students' learning. Inquiry addresses the development of understanding through gathering and using evidence. But although the ideas developed through inquiry can begin from the students' pre-existing ideas, inquiry does not necessarily require this. Nor does it require student self- and peer-assessment. Constructivism, on the other hand, emphasises that development starts from the ideas and skills that students bring from their previous experience and the role of evidence and argument with others in the creation of more scientific ideas but says little about gathering evidence, the nature of progression or the role of students' self- and peer-assessment. Formative assessment adds the importance of regulating teaching to keep pace with learners' understandings. It has at its centre the involvement of students in their own learning, giving them the information and skills they need to assess their progress in relation to their goals and to take responsibility for their own learning.

Teaching with big ideas in mind

Yet there is still something missing – the explicit reference to the development of big ideas. The question must be asked: what differences in pedagogy would be associated with working with big ideas in mind?

Suppose that there is in place pedagogy that provides opportunities for inquiry, is based on a constructivist view of learning and incorporates formative assessment strategies, what difference would it make to have the overall goals of learning science identified in terms of development towards big ideas?

A first step would be for the teacher to be aware of the link between the goals of a lesson or series of lessons and the development of a big idea. However 'small' are the ideas that can be developed in lessons on a topic, it should be possible to see them as steps (vertical, horizontal or spiral – see Section 3) towards a big idea. For instance, planting seeds and stones in soil to see if they grow sets students thinking about differences between living and non-living things, eventually leading them, some years later, to recognise the cellular structure unique to living organisms.

It is easier to see links between the goals of particular activities and big ideas in the programmes of older students because the ideas developed in activities are likely to be already bigger. For very young children it may be difficult to judge any activity as being *not* relevant to big ideas of science since broad interpretation is intended. However the time spent on different activities ought to reflect their importance in developing overall understanding. So having big ideas of science in mind will mean that:

- Teachers will be spending more time to allow students to study in depth certain objects, events, or phenomena, appropriate to their age and development. These topics of study will be selected so that they have, to the teachers and any observer, a clear relationship to one or more big ideas. They will enable understanding at an appropriate point in the progression to big ideas. Thus teachers will be able to explain how the ideas the children develop through the activities in which they are engaged relate to the overall big ideas and so justify the time they are spending on it.

Teachers will allow students to study in depth certain objects, events, or phenomena selected so that they have a clear relationship to one or more big ideas

But just because a link exists in theory does not mean that the activities are effectively contributing to the overall understanding summarised in the big idea. This contribution depends on teachers helping the students to make links that create bigger and more abstract ideas. The progression in the development of ideas towards greater abstraction is one of the main areas of difficulty in science teaching. Science begins with observation of our surroundings – a stone, the Moon, a plant – and proceeds through progressive generalisation of experience to more abstracts categories or ideas – force, gravitation, atom. At these levels of abstraction common sense is no longer useful, and mathematical formulations or other symbols are needed. Teachers need to be aware of the successive steps of abstraction and ensure that students are able to take these steps recognising that the more abstract ideas deepen understanding of everyday observations. Thus:

- Teachers will be making students aware of how the ideas that are emerging from their classroom inquiries relate to things in their daily lives. They will help students to recognise links between new and previous experiences; between new and previous ideas. The recognition of these links makes science an exciting experience.
- Teachers will be consciously building students' understanding into big ideas, thereby ensuring that the students arrive at a picture of the world that is not a collection of independent assertions but parts that connect with each other. Without making the links and realising the coherence of ideas, science is fragmented. Just as a house is not a pile of bricks, so science is not a pile of disconnected facts.

Just because a link exists in theory does not mean that activities are effectively contributing to the overall understanding summarised in the big idea

- Through discussion of current scientific investigations students become aware of the universality of scientific ideas and their application in understanding both very large scale and very small scale phenomena.

At the same time as developing big ideas of science, students should be developing ideas about science. Key to this is the conscious realisation of the importance of evidence to support students' developing ideas of science, leading later to recognition of the evidence base for the big ideas. Thus:

- The way in which teachers engage with students will encourage students to recognise that they need evidence to support their claims and ideas. Students will be helped to recognise that facts are not a matter of opinion but may still change or be refined in the light of new evidence.
- Teachers will help students to decide how to collect and interpret data and to use it as evidence in answering their questions. Students' awareness of these processes will be raised through discussion of their own and others' investigations and examples of how scientists test ideas.
- The discussion of events in the history of science will be used to show how evidence has or has not been used in the past to develop ideas and how developments in technology have advanced scientific understanding and vice versa.

Big ideas and teachers' understanding in science

Primary school teachers face particular challenges in relation to big ideas in science. First, the activities of young children are generally focused on exploring their local environment and the living and non-living things in it. Their investigations and observations lead to small ideas whose connection to big ideas of science may seem tenuous. But in many cases teachers' own education in science has left them without a personal grasp of big ideas and little opportunity to understand how the pieces of information they do have can be linked together. They are, therefore, likely to be poorly equipped to see the links between the ideas developed in classroom activities and the more widely applicable ideas and so not in a position to help children progress toward these ideas. A further difficulty is lack of confidence in teaching science as a result of little personal experience and understanding of scientific activity.

Primary teachers face particular challenges … in many cases their own education in science has left them without a personal grasp of the big ideas and little opportunity to understand how the information they do have links together

In the secondary school the links between learning activities and big ideas are likely to be rather more obvious. But secondary teachers can also suffer from limited knowledge in particular science domains – being trained in biology, for example, but having to teach physical sciences – and from lack of first-hand experience of genuine scientific activity that would give confidence in teaching ideas about science.

For all teachers, the ideal would be personal understanding of big ideas of and about science. If they lack this as a result of their own school science education what hope is there of acquiring it during initial teacher education or continuing professional development? Of course, the whole of science education cannot be condensed into the limited time available in pre- or in-service teacher education courses. But teachers and trainees are intelligent adults. They have wide relevant experience and knowledge to a greater extent than they often realise. As adults – and it should be emphasised that this is not an approach appropriate for school students – engaging with big ideas in broadly descriptive form can help them make sense of their experience. It can enable them to bring together fragments of recalled knowledge and indeed can lead to pleasure in making sense of things that previously seemed beyond their comprehension.

Understanding of science and how to teach particular concepts can be provided through direct contact with more experienced teachers and scientists, through links with university science students and through the internet

The 'engagement' here is far more than reading and discussing the narrative descriptions of big ideas. It ought to be a form of inquiry in which learners draw on their experiences and those of others as evidence in making sense of the evolving 'story'. Socially co-constructing their ideas in this way is unlikely to lead to a full grasp of big ideas but will hopefully begin an on-going process of deepening understanding and one which enables teachers to help students in their progress.

This experience should be matched by engagement of teachers in learning some science through inquiry at their own level in order to develop understanding of scientific inquiry through participation in it. It requires that some time is spent giving teachers and trainees opportunity to question and investigate something quite simple in their everyday lives (such as why paper towels are made up of several layers; why ice floats; why the outside of a can of drink becomes moist when it is taken out of a fridge). In these activities teachers are not asked to role-play, but to become genuine investigators of these common phenomena. Reflection on what they understand initially, what more they find out, and how, can lead them to an insight into how science works.

Just as important as such first-hand experiences in teachers' courses is the provision of continuing support for developing of understanding of science and of effective pedagogy in a form that can be accessed throughout their active lives. Personal understanding of science and how to teach particular concepts can be provided, for instance, through direct contact with more experienced teachers and scientists, through links with university science students who work with groups of students in classroom or laboratories and through the internet. To optimise this support all those involved should be prepared for their role by having big ideas in mind and sharing the aim of developing students' progressive understanding of them.

In conclusion

In this report we have set out the principles that we consider should underpin the science education of all students throughout their schooling. A key principle is that students should be helped to develop big ideas of science and about science that enable them to understand the scientific aspects of the world around and make informed decisions about the applications of science. For this understanding students need learning experiences that are interesting and engaging and seen as relevant to their lives. We have considered the progression from small ideas about specific events, phenomena and objects to more abstract and widely applicable ideas and proposed significant aspects of pedagogy that are required to support this progression.

We are well aware that the work is far from definitive, but we hope that by making what we have achieved available to others it will stimulate further thinking about the goals and procedures of science education that is fit for purpose in the twenty-first century.

Seminar Participants

From left to right: Rosa Devés, Pierre Léna, Wynne Harlen, Hubert Dyasi, Derek Bell, Patricia Rowell, Robin Millar, Wei Yu, Michael Reiss, Guillermo Fernández de la Garza

Derek Bell

Professor Derek Bell is Head of Education at The Wellcome Trust. He has held several posts in schools and colleges in England and was for six and a half years Chief Executive of the Association for Science Education (ASE). He was awarded a professorship by the College of Teachers in July 2007. Throughout his career he has maintained a strong and active interest in the enhancement of teaching and learning in science and exploring ways to help children develop their understanding of the world around them. He was a member of the SPACE (Science Processes and Concept Exploration) project team in the 1980s and went on to coordinate the Nuffield Primary Science Project which developed from the SPACE research. His research interests include children's understanding in science, in particular those children with learning difficulties. His research on curriculum leadership and the role of science coordinators in primary schools is encapsulated in *Towards effective subject leadership in the primary school*, which was first published in 1999 by Open University Press.

Derek has undertaken a wide range of consultancies in the UK and overseas and has been a member of several advisory/expert panels including the STEM High Level Strategy Group, National Coordinators Group for the National Network of Science Learning Centres, the WISE National Co-ordinating Committee and the Astra-Zeneca Science Education Forum. He is currently a board member of the Engineering Technology Board (ETB) and STEMNET. He is keen to enhance the links between science, technology, engineering and mathematics through new and existing partnerships across the education, industrial and business sectors.

Rosa Devés

Professor Rosa Devés is Provost at the University of Chile in Santiago and since 2003 she has been a member of the Chilean Academy of Sciences. She graduated in Biochemistry in 1974 at the University of Chile and received a PhD in biochemistry from the University of Western Ontario, Canada. In 1980 she joined the Department of Physiology and Biophysics at the Faculty of Medicine of the University of Chile. She teaches at undergraduate and graduate level in cell physiology and physical chemistry and has participated actively in the development of graduate education including the founding of an influential PhD programme in Biomedical Sciences which she directed for two periods of five years. She also has been Director of Graduate Studies of the University.

In 2000 she was called by the Curriculum and Evaluation Unit at the Ministry of Education to act as coordinator of the science teams that were developing the new curriculum. This began her involvement in education at the school level, while she continued full time at the university. In 2002, she became aware of the inquiry based science education programme that was being advocated by the National Sciences Resources Centre in the USA and collaborated with Jorge Allende in the establishment of the ECBI Inquiry-based Science Education Programme, which started in six public schools with 1000 children. Since then, the programme expanded to encompass 250 schools in all regions of the country who work in partnership with twelve Chilean universities, the Ministry of Education and the Academy of Sciences to bring high quality science education to all children.

Hubert Dyasi

Professor Hubert M. Dyasi is an internationally recognised professor of science education specialising in the professional development of teachers of science. He received his PhD in science education at the University of Illinois at Urbana-Champaign. He has taught undergraduate and graduate science education courses and supervised school-based student teachers nationally and internationally. During 1966-1970, as a member of the faculty of Njala University College of the University of Sierra Leone (West Africa) he was Executive Director of the African Primary Science Program and the Science Education Programme for Africa 1970-1983, serving almost all of sub-Saharan Africa.

From 1984 to 2004 he directed the City College Workshop Centre in New York, developing it into a highly respected local, national, and international science education and general education development organisation. In addition to directing science teacher education programmes serving New York City school districts, he has collaborated with the New York State Education Department and nationally with schools and school districts to develop their science education programmes and to implement science inquiry education in classrooms. He has been a member of numerous advisory boards and a consultant on the teaching and learning of science and served on various panels and visiting teams of the National Science Foundation.

Among his academic achievements are: Visiting Fellow of All Souls College and Academic Visitor at the University of Oxford; Visiting Scholar at the California Institute of Technology; Fellow of the National Institute for Science Education; and member of the National Research Council's Committee on Science Education K-12. In 2005 he received the Exploratorium's Outstanding Educator Award, and the national Science Teachers Association’s Distinguished Service to Science Education Award in 2008. His scholarly work includes contributing chapters to and co-authorship of several books including *Linking Science & Literacy in the K-8 Classroom*, (2006), *America's Lab Report* (2005), *Teaching Science in the 21st Century* (2005), *Designing Professional Development for Teachers of Science and Mathematics* (2003), *The National Science Education Standards* (1996), *Inquiry and the National Science Education Standards: A Guide for Teaching and Learning* (2000).

Guillermo Fernández de la Garza

Guillermo Fernández de la Garza is President and Chief Executive Officer of the United States - Mexico Foundation for Science (FUMEC), an endowed non-profit organization sponsored by the United States and the Mexican Governments. In FUMEC he has worked to develop binational regional innovation clusters in areas such as aerospace, ITC and advanced manufacturing, as well as facilitating innovation in medium and small businesses. He has bachelors degrees in Engineering and in Physics from Mexico's National Autonomous University, a masters degree in Engineering Economics from Stanford University and completed advanced studies in Nuclear Engineering and Business Administration of IPN and IPADE. He has worked in innovation programmes in industry, universities and government.

Guillermo has made notable contributions to the popularization of science and to science education. He was a founding member of the Mexican Society for Science and Technology Popularization (SOMEDICYT) and convener of a team of scientists, educators and business leaders which founded CHISPA - a science magazine for children that was published monthly in Mexico from 1978 to 1998. CHISPA won Mexican and international awards. Books with selections of articles from the Magazine are still distributed by the Mexican Ministry of Education. The Meetings of children and scientist that CHISPA organized evolved to become the “Saturdays and Sundays in Science” programme that has been operated by the Mexican Academy of Sciences.

He organized jointly with the Ministry of Education and the Mexican Academy of Science the initial testing activities in Mexico of the Science and Technology for Children curriculum of the National Science Resources Centre. In 2002, with the support FUMEC, he initiated the setting up of INNOVEC, Innovation in Science Education, a non-profit organization that has been instrumental in the application of the Inquiry-Based Science Education systems in Mexican public schools. Presently INNOVEC has agreements with the Mexican Ministry of Education and 10 State Governments to bring this kind of education to more than 300,000 children, organising international conferences, workshops, training and advice programmes for teachers, pedagogical advisers, and education authorities. Guillermo was awarded the 2008 PuRkwa Prize offered by the French Academy of Science and the Saint Etienne Mining School for innovative practices in science education.

Wynne Harlen

Professor Wynne Harlen has held several posts as teacher, teacher educator and researcher in science education and assessment since graduating from Oxford with a physics degree. In 1985 she was appointed Sydney Jones Professor of Education at the University of Liverpool, at the start of five of the most active years in primary science. She was a member of the Secretary of State’s Working Group in science which produced the first draft of the National Curriculum England. She negotiated a large grant from the Gatsby Trust to set up in Liverpool a Centre for Research and Development in Primary Science, which continues to flourish. She led several projects in research, professional development and curriculum development, including the joint Liverpool-King’s SPACE (Science Processes and Concept Exploration) project, co-directed with Paul Black, resulting in the SPACE research reports and the Nuffield Primary Science materials.

In 1990 she moved to Edinburgh to become Director of the Scottish Council for Research in Education. Since 1999 she has been Visiting Professor of Education at Bristol University although essentially working from home in Scotland.

Wynne has been a life-long, and now honorary, member of the UK Association for Science Education (ASE), edited Primary Science Review 1999-2004, and was its president in 2009. She was chair, OECD PISA Science Expert Group, 1998-2003 and of a working group of the Royal Society

(State of the Nation Report on Science and Mathematics Education 5-14). She now chairs the International Oversight Committee of the Inter Academies Panel Programme on Science Education.

She was awarded the OBE by the Queen for services to education in 1991 and was given a special award for distinguished service to science education by ASE in 2001. In 2008 she was awarded, jointly with Guillermo Fernández de la Garza, the International PuRkwa Prize 'for the scientific literacy of the children of the planet'.

Pierre Léna

Professor Pierre Léna has been professor of physics and astrophysics at the Université Paris VII (now the Université Paris Diderot). Associated with the Observatoire de Paris, he has contributed to the development of infrared astronomy, to the design of the European Very Large Telescope (VLT) in Chile, to new optical techniques applied to astronomical images (adaptive optics and interferometry). He directed the graduate school pf Astronomie and Astrophysique d'Ile-de-France for many years and advised many PhD students. He became a member of the French Académie des Sciences in 1991, and later of Academia Europeae and the Pontifical Academy of Sciences.

His involvement in education developed beside his duties as university professor, when he became Chairman of the French *Institut national de recherche pédagogique* (1991-1997) and encountered issues relating to the training of science teachers. When Georges Charpak, after his Nobel prize (1992), decided to propose a large reform of science education in French primary schools, Pierre joined the movement together with the physicist Yves Quéré. The French Académie des sciences, of which these three scientists were members, fully supported the movement. Thus the inquiry-based project *La main à la pâte* was established. The project first impacted French schools on a small scale, developing classroom procedures and resources, before being recognised officially in the French curriculum in 2002. The project expanded internationally after 2000 (www.lamap.fr). In 2006, the project, still supported by the Académie, began an extension in middle schools, under a contract with the Ministry of Education.

The success of these enterprises led the Académie to establish at the end of 2005 a special permanent office, the Délégation á l'éducation et la formation to manage these projects which were extended to include teacher training. The role of the Academie is toto offer opinions and advice to the government bodies involved. Pierre has directed this Delegation since 2006. There are between 20 and 30 members of staff, all dedicated to science education, international cooperation and a limited amount of research. Books and other resources are published every year, training session organised and advice provided to various ministries.

www.academie-sciences.fr/enseignement/generalites.htm

Robin Millar

Professor Robin Millar is Salters' Professor of Science Education at the University of York, England. With a degree in physics and a PhD in medical physics, he trained as a teacher and taught physics for eight years before moving to the University of York in 1982 as a Lecturer in Education. In the Department of Educational Studies at York, he teaches on the undergraduate education course, the initial teacher education (PGCE) programme for beginning science teachers, and on the master's programme and also supervises the project work of students (mainly teachers) studying for MA and PhD degrees.

He has written and published widely on many aspects of science teaching and learning, his main areas of research interest being: students' learning in science; curriculum design and development in science, particularly the implications of a focus on scientific literacy for curriculum and teaching;

and the relationship between research and practice in science teaching. He has directed major research projects on investigative practical work in science, and on young people's images of science. From 1999-2004, Robin was coordinator of the *Evidence-based Practice in Science Education* (EPSE) Research Network, funded by the UK Economic and Social Research Council. The EPSE Network carried out four inter-related projects exploring ways of increasing the impact of research on practice in science education.

He has been involved in several major curriculum development projects. He was a member of the management and writing teams for *Salters' GCSE (General Certificate of Secondary Education) Science*, and of the Advisory Committee for *Salters Horners A-level Physics* and co-directed the development of an innovative AS-level course called *Science for Public Understanding,* and the *Twenty First Century Science* suite of GCSE courses.

Robin was a member of the UK group in the European Union *Labwork in Science Education* project from 1996-2000, and a member of the Science Expert Group for the OECD *Programme for International Student Assessment (PISA)* from 2003-2006. He was President of the European Science Education Research Association (ESERA) from 1999-2003 and is currently a member of the Scientific Advisory Committee of the Leibniz Institute for Science Education (IPN), the leading science education research and development centre in Germany.

http://www.york.ac.uk/depts/educ/people/MillarR.htm

Michael Reiss

Professor Michael Reiss holds the Chair of Science Education at the Institute of Education, University of London where he is also Associate Director for Research, Consultancy and Knowledge Transfer. He has a first class degree in Natural Sciences and a PhD and post-doctoral qualification in animal behaviour and evolutionary biology from the University of Cambridge. He trained as a teacher and spent five years teaching science (mainly biology) and some mathematics in the state school sector before returning to higher education in 1988.

His particular interests in science education are in the aims of science education, the design of curricula and the factors that cause students to want to continue with science. He has held many research grants from a wide range of funders and is author or co-author of a number of books on science education including several on ethical and moral issues, sex education, evolution and learning science outside the classroom.

Michael was Vice President of the Institute of Biology (1994-97), a Member of the Advisory Committee on Novel Foods and Processes (1998-2001), Chair (2000-01) of EuropaBio's External Advisory Group on Ethics, the Specialist Advisor to the House of Lords Select Committee on Animals in Scientific Procedures (2001-02), Visiting Professor at Kristianstad University (2002) and Director of Education at the Royal Society (2006-08). He is currently Vice President of the British Science Association, Chief Executive of Science Learning Centre London, Honorary Visiting Professor in the Universities of Birmingham and York, Docent at the University of Helsinki, Director of the Salters-Nuffield Advanced Biology Project, a member of the Farm Animal Welfare Council and editor of the journal *Sex Education*. He is a Fellow of the Society of Biology and of the Royal Society of Arts and an Honorary Fellow of the British Science Association and of the College of Teachers. He has an MBA, worked professionally, part-time, as a Counsellor for ten years and has been a Priest in the Church of England for 20 years.

www.reiss.tc.

Patricia Rowell

Professor Patricia Rowell is Professor Emeritus in Science Education at the University of Alberta Canada. Her research interests focus on curriculum development, teacher development and the role of language in school science, and in 2001-2, she was a McCalla Research Professor at the University of Alberta. Patricia has bachelors and masters degrees in biochemistry from University College London and the University of Oxford and a doctorate in Science Education from the University of Alberta.

She has participated in science education projects in Uganda, Botswana, Namibia, South Africa, Australia and China. She was funded by the Canadian International Development Agency (CIDA) as a visiting professor at the University of Botswana for two years, where she pioneered qualitative classroom studies in addition to her teaching responsibilities. With USAID, she was appointed as Senior Technical Advisor to the Government of Namibia for two years, with responsibility for primary science curriculum development. Subsequently, as Project Director of a University of Alberta-CIDA teacher education project in Namibia, she worked closely with Namibian college faculty on their science education programs. Her contributions to CIDA-funded teacher development projects in Uganda and China included the presentation of courses, workshops, materials development and supervision of graduate students. A publication for Chinese science teachers co-authored with Prof Wei Yu has been widely distributed, as have classroom materials for elementary school science in Namibia, Eastern Cape, and Western China.

As a member of the Interacademy Panel Working Group on Science Education, she has collaborated with a group of international science educators and academicians to support inquiry-based science education (IBSE) in developing countries. At the invitation of the Chilean government, she was a member of the international evaluation team, with Professors Harlen and Léna, for the inquiry-based school science programme in that country. She is also collaborating with the Centre for Research in Learning Science at Southeast University in Nanjing, which is spearheading primary science education reform across China.

Wei Yu

Professor Wei Yu, born in China, has a doctorate in Electronic Engineering from Aachen Technical University, Germany. After graduating from Nanjing Institute of Technology in 1965, she became a research fellow in the Institute of Electronics, NIT. She was selected as the one of the first groups to undertake further study in West Germany at 1979, becoming the first woman PhD in New China. After she returned to China she founded the Department of Biomedical Engineering and the Laboratory of Molecular and Biomolecular Electronics (LMBE) in Southeast University. From 1984 to 1993 she was the Director of LMBE and President of Southeast University. She has received honorary degrees from eight universities outside Mainland China.

During her long career as a teacher and researcher in electronics, her significant achievements included the development of bioelectronics and grounding molecular and biomolecular electronics. She also made important contributions to the reform of higher education and distance learning in China during 1993-2002 when she was the vice-minister in Ministry of Education. From 1994 to 2002 she was a member of ICSU-CCBS (International Council of Scientific Unions-Committee of Capacity Building on Science).

Since 2001 Wei Yu has founded a new interdisciplinary research – the Science of Learning, the frontier area of Mind, Brain and Education in China – bridging neuroscience and education. At the same time she introduced *Learning by Doing* an inquiry-based approach to science education into China and founded the website www.handsbrain.com. Based on her contribution to *Learning by Doing* in 2006 she was awarded the PuRkwa prize by the French Academy of Sciences and the Saint

Etienne Mining School for innovative practices in science education. In 2007/8 she chaired the committee revising the National Standard of Science Education in Primary Schools in China, which were presented to ministry of education at the end of 2009.

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