Working with Big Ideas of Science Education

Edited by Wynne Harlen

with Derek Bell, Rosa Devés, Hubert Dyasi,
Guillermo Fernández de la Garza, Pierre Léna,
Robin Millar, Michael Reiss, Patricia Rowell and Wei Yu

the global network of science academies

Published by the Science Education Programme (SEP) of IAP

www.interacademies.net/activities/projects/12250.aspx

IAP - c/o ICTP campus - Strada Costiera, 11 - 34151 - Trieste - Italy

www.interacademies.net
iap@twas.org

[ISBN no.]

Working with

Big Ideas

of Science Education

Preface

In 2009 a group of experts in science education took part in an international seminar 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. An overcrowded and fragmented science curriculum was recognised as one of several factors in students' perception that science was a disconnected series of facts of very little wider meaning. Part of the solution to this problem was to conceive the goals of science education, not in terms of the knowledge of a body of facts and theories, but as a progression towards understanding key ideas – 'big ideas' – of relevance to students' lives during and beyond school. The seminar and subsequent work by the group resulted in the publication of *Principles and Big ideas of Science Education*, which was freely distributed, translated into several languages and received a good deal of interest across the world.

Five years on, the initially identified reasons for a focus on developing big ideas in science remain but other reasons have emerged, adding to the compelling rationale. A second international seminar, attended by the same group of science experts, augmented by an expert on curriculum change, was convened to review the earlier work. The seminar, in September 2014, was funded by a generous contribution from the Ministry of Education of Mexico, for INNOVEC international collaboration activities, by contributions from the institutions of some of the participants and from some individuals. All participants took active roles in the two and a half day seminar and in subsequent review and refinement of this publication. A detailed record was kept of the seminar presentations and discussions. As before, the range of experience and cultural backgrounds of the members of the group will hopefully extend the relevance of the work for science education in different parts of the world.

For this joint effort grateful thanks are due to the expert group: Derek Bell, Rosa Devés, Hubert Dyasi, Guillermo Fernández de la Garza, Louise Hayward, Pierre Léna, Robin Millar, Michael Reiss, Patricia Rowell, Wei Yu; and to Juliet Miller (rapporteur).

Executive Summary

The purpose of this publication is to update the discussion and conclusions about the essential understanding in science that all students should acquire during the compulsory years of school. It follows five years after *Principles and Big Ideas of Science Education*[1] was written in response to concerns that many students did not find their science education interesting or see it as relevant to their lives. Part of the problem was an overcrowded curriculum that appeared to be a set of disconnected facts to be learned; thus part of the solution was to conceive the goals of science education, not in terms of the knowledge of a body of facts and theories, but as a progression towards understanding key ideas of relevance to students' lives during and beyond their school years. These are identified as the 'big ideas' that should be understood by all students – not just those who go on to study science or take up science-based occupations beyond school – and equally by all, regardless of gender, cultural background or disabilities.

Principles and Big Ideas of Science Education, resulting from an international seminar of expert scientist and science educators in 2009, identified some guiding principles, ten big ideas of science and four ideas about science and its applications. *Working with Big Ideas of Science Education* – resulting from a further seminar and work by the same group – adds to the earlier work in setting out in greater detail the rationale for working towards big ideas and the implications of this for curriculum content, pedagogy, student assessment and teacher education.

As well as the continuing importance of factors relating to students' and teachers' perceptions of science, which prompted the initial work, several other factors can be identified relating to the potential benefits for students as individuals in an age of innovation and benefits for society. For individual learners there are benefits from being able to grasp the essential features of events or phenomena in the world around that enable them to make informed decisions affecting their own and others' health and wellbeing. Society benefits from citizens making informed decisions about matters such as energy use and care for the environment.

Science education also needs to take account of changes in the work place that require ability to link science with engineering, technology and mathematics (STEM), the urgent need for attention to major global issues such as the adverse impacts of climate change, the positive and negative influences of student assessment and the growing contribution of neurosciences to the understanding of learning. All of these add to the reasons for the development of big ideas to provide a framework for decisions about science education.

Whilst the multiple goals of science education are recognised in the underlying principles, the focus here remains on conceptual understanding with the development of scientific capabilities and attitudes embedded in appropriate pedagogy rather than as separate lists

---

1 *Principles and Big Ideas of Science Education* Edited by Wynne Harlen with the contribution of Derek Bell, Rosa Devés, Hubert Dyasi, Guillermo Fernández de la Garza, Pierre Léna, Robin Millar, Michael Reiss, Patricia Rowell and Wei Yu. Published by the Association for Science Education, 2010. ISBN 978 0 86357 4 313.

of goals. The big ideas *of* science and *about* science are expressed in the form of narrative descriptions of a progression that builds up understanding of key ideas across the years from the start of primary to the end of secondary school.

The implication of putting into practice principles and big ideas are considered in relation to the selection of content, pedagogy, student assessment and teacher education. In relation to pedagogy it is argued that not only does inquiry have a central role in developing understanding but that identifying big ideas in science is a necessary accompaniment to promoting inquiry-based science education. A final section on implementation discusses what is needed to bring about change in practice, including how ideas are expressed in the science curriculum, developing teachers' understanding of big ideas and evaluating teaching for big ideas.

1 Introduction and rationale

Introduction

The five years since the publication of *Principles and Big ideas of Science Education* show evidence of the rapid changes taking place in education generally and science education in particular. Students are using digital technologies inside as well as outside the classroom; new frameworks for the curriculum are being implemented; computers are being used to extend the range of assessment; and there is further advance in understanding learning and how to bring it about.

Even greater changes, with enormous implications for education, are taking place in the world of work, where technology has made certain types of work unnecessary. The opportunities for middle level labour are diminishing, leaving those occupations which are difficult to automate – mainly lower-level jobs and higher level work that requires uniquely human capabilities. For many, ability to create new products, solve problems and undertake complex tasks will – at least for the moment – be the route to avoiding unemployment with all its social consequences. Globalisation introduces opportunities but also challenges, particularly for those in parts of the world less able to change as rapidly as highly developed countries.

To prosper in this modern age of innovation requires the capacity to grasp the essentials of diverse problems, to recognise meaningful patterns, to retrieve and apply relevant knowledge. Science education has the potential for helping the development of the required abilities and understanding by focusing on developing powerful ideas of science and ideas about the nature of scientific activity and its applications. Recognising this provides part of a strong rationale for revisiting the big ideas identified in 2009 and particularly the implications for change in science education practice required for their implementation.

Finally, the global issues faced by humanity, such as climate change, health and population growth, create an urgent need for young people to have a basic understanding of the relevant scientific ideas, technological and ethical issues and powers of reasoning, to be prepared to face these issues.

We now turn to review the rationale for the importance of identifying big ideas and note some associated challenges and benefits.

Rationale

Five years ago we identified these reasons for making explicit the core ideas that should be the goals of science education:

- to respond to students' perceptions of science as a fragmented collection of facts and theories of little relevance to them, by building ideas into a coherent picture of how the world works

- to provide a basis for classroom activities that help students to explain things they find important
- to provide a basis for selection from the enormous range of possible curriculum content
- to inform the development of curriculum frameworks built on progression towards big ideas.

These reasons continue to apply but now there are others to add, briefly discussed here but fleshed out in later discussion. They arise from three directions:

- widespread embrace of inquiry-based pedagogy in science education
- recognition of the connectedness of science and other STEM subjects[2] in daily life contexts
- greater understanding being provided by neuroscience of conditions that influence learning.

Inquiry-based science education

Inquiry-based pedagogy is being embraced in principle across the globe, supported in the last decade by an increasing body of research on its effectiveness. Learning science through inquiry involves learners developing understanding through their own mental and physical activity, starting from their existing ideas and, through collecting, analysing and interpreting evidence, developing more powerful and scientific ideas to explain new events or phenomena. It embodies a social constructivist view of learning and involves students working in ways that are similar to those of scientists, thus developing some appreciation of the nature of scientific activity. Although not all science learning can be or needs to be through inquiry, it has a key role in helping students to develop understanding. However, implementing inquiry effectively is time consuming and so there has to be a choice of those topics and activities that make best use of limited and precious learning time. The selection of the key powerful ideas that are more useful in understanding the world around is thus a corollary to seriously adopting an inquiry-based approach to teaching and learning in the compulsory years of school.

Connections in daily life

Situations where science is used in daily life, and which are likely to capture the interest of many students, often involve combining science with other subjects, particularly engineering, technology and mathematics. Changes in the workplace, and in research

---

2 Science, Technology, Engineering and Mathematics. We take the meaning of these to be:

Science: the ideas about the natural world, warranted by empirical evidence, that have been accumulated over time and the processes by which these ideas have been generated.

Technology: the systems, processes and artefacts produced by human beings to serve their needs or desires.

Engineering: the systematic and iterative process, informed by scientific knowledge, of designing objects and systems to achieve solutions to human problems.

Mathematics: the systematic study of patterns and relationships among quantities, numbers and space expressed symbolically in the form of numerals and forms and warranted through logical argument.

activity, increasingly require multidisciplinary/transdisciplinary teams to tackle a broad range of scientific and problems that may have implications for society. Real world contexts and problems – such as designing sustainable energy systems, bio-medical engineering, maintaining biodiversity in areas where conflicts arise between local and global needs – demand knowledge, concepts and skills from several disciplines. A general understanding of the issues and of their ethical implications is needed by all citizens if the political will is to be mobilised to solve the problems they present. These considerations raise questions of how to ensure relevant learning by all students, whether or not they will later be employed in such enterprises.

It follows that being able to see the connections between different ideas in science, as in the understanding of big ideas and how they were developed, is an important part of preparation for work and life. Education that helps students to connect ideas across and within subject domains encourages creativity and innovation. It prepares students to participate in, rather than being at the mercy of, the rapid changes in occupations and communication using technologies developed through engineering and the applications of science.

Neuroscience and research into cognition

Advances in research into the activity of the brain are rapidly identifying factors that facilitate effective learning. A relevant finding is that ideas that are connected are more readily used in new situations than unconnected ideas. This provides support for working towards a few big ideas that enable understanding of the world and our experiences in it, rather than a series of disconnected items of knowledge. Building connections and recognising patterns enable learners to identify significant aspects when trying to understand new situations. Brain imaging reveals how grasping new ideas is accompanied by an emotional reaction showing that there is pleasure in developing understanding. Pedagogy that involves learning in groups and watching others who are more expert also finds support from identifying the activity of mirror neurons. While extravagant and unvalidated claims are sometimes made for the contribution of neuroscience to education, it does seem likely that more scientifically-based contributions will increasingly be forthcoming, with direct classroom applications not only to science education but to other subjects too.

Challenges

At the same time as acknowledging the strong case for focusing teaching on big ideas, it is important to recognise that some developments over recent years have created challenges, or indeed obstacles, to the changes that are needed for students to have the chance to develop understanding. Two key challenges concern student assessment and teacher education.

Student assessment

In many countries there has been a constant increase in testing and the use of test results to set targets for teachers and schools, in the false belief that this will improve learning. Conventional tests and examinations present a series of disconnected questions or problems, which all too often encourage teaching of disconnected pieces of knowledge. If progress towards big ideas is to be effectively supported and assessed there has to be a fundamental change in the ways in which data about what students are able to do are generated, collected and used. Without this, the impact of assessment on what is taught and how it is taught will restrain, even strangle, attempts to help students develop key abilities and understanding.

Teacher education

When planning lessons it is important for teachers to have in mind how the goals of individual lessons fit into a wider picture of more powerful ideas that can help students make sense of a broad range of related phenomena and events. Having this general direction of development in mind frames what teachers observe and look for in students' actions, questions and talk, and will inform their decisions about feedback to students and how to adapt their teaching through formative assessment to support students' further learning. This is particularly challenging for primary school teachers, who must teach all subjects, but equally for some secondary school teachers who teach all science domains but may have studied only one or two in depth. Many teachers' own education in science at school lacked involvement in scientific activity and the opportunity of developing the big ideas. Teacher education should supply this experience if teachers are to be equipped to help students progress towards the goal of understanding these ideas.

Benefits for individuals and society

If we can meet these challenges there are important benefits for students as individuals and for society. Benefits for students derive from those of any well-designed programme of study. In science these include the satisfaction of being able to make sense of the world and appreciation of the nature of scientific activity and its impact on our lives. The added benefit from the development of powerful ideas which have wide application in a range of experiences follows from being able to grasp the essential features of events or phenomena even though lacking the knowledge of every detail. Understanding aspects of the world around helps individuals in their personal decisions that affect their health and enjoyment of the environment as well as their choice of career. The practice of questioning, seeking evidence and answers, and sharing views with others also contributes to building confidence and respect for themselves and others. Furthermore, the satisfaction of being able to see patterns in different situations and connections between them provides important motivation for learning during and beyond formal education.

Benefits for society follow from young people developing understanding of key ideas that enable them to make informed choices both as students and later in life about, for instance, their diet, exercise, use of energy and care of the environment. As well as impact on their own daily lives, such matters have wider implications for their and others' future lives through longer-term impact of human activity on the environment. Understanding 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, the use of scientific knowledge in engineering and technology, can impact both positively and negatively on society. Education in science has a unique role in creating understanding and the will to tackle the issues that lead to inequalities in wealth, employment, health and education across the world.

2 Principles

Implied in the rationale for focusing on core ideas of science are certain principles relating to science education. Stating them explicitly makes clear the values and standards that have guided our decision about big ideas and about how to put them into practice. As a result of reviewing the principles identified in *Principles and Big Ideas of Science Education* we have found no reason to make any substantial changes in them. However, we concluded that it may be helpful to restate them here more briefly and as more clearly applying to particular aspects of science education.

Principles applying to the aims of science education

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 provide every student equally with opportunities that enable them to take an informed part in decisions, and to take appropriate actions, that affect their own wellbeing and the wellbeing of others and the environment. 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 applications**
- **scientific capabilities concerned with gathering and using evidence**
- **scientific attitudes and dispositions.**

Science education should enhance learners' curiosity, wonder and questioning, building on their natural inclination to seek meaning and understanding of the world around. Scientific inquiry should be introduced and encountered by school students as an activity that can be carried out by everyone including themselves. They should have personal experiences of finding out about and of making connections between new and previous experiences that not only bring excitement and 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.

For learners as individuals, science education should help them to develop the understanding, powers of reasoning and attitudes that enable them to lead physically and emotionally healthy and rewarding lives. It should enable them as 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.

Through science education, students should develop understanding of big ideas about objects, phenomena, materials and relationships in the natural world. Science education should also develop big ideas about scientific inquiry, reasoning and methods of working and ideas about the relationship between science, technology, society and the environment. Although the big ideas *of* science (resulting from scientific activity) and *about* science (how we perceive and use science) form the main focus of this publication, the goals of science education should also include the development of scientific capabilities and scientific attitudes.

Principles applying to the selection of learning activities

Programmes of study should indicate a clear progression towards the goals of science education, based on current research and understanding of how learning takes place. Progression towards big ideas should result from study of topics of interest and relevance to the lives of students of all backgrounds. Diversity among students should be used to enhance the learning of all.

Learning activities should enable students to experience science and scientific inquiry in accordance with current scientific and educational thinking. They should deepen understanding of scientific ideas as well as having other possible aims, such as fostering attitudes and capabilities.

Students bring to school ideas formed about the world through their actions, observations and thinking in their daily lives. These need to be the starting points for the development of the understandings, capabilities and attitudes that are the goals of science education. Students of different backgrounds should have opportunities to learn from activities of interest to them and relevance to their experience.

Progress towards goals should be informed by what is known 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.

Learners find it very difficult to learn with understanding from tasks which have no meaning that is apparent to them. They learn more effectively when they can link new experiences to what they already know and are motivated by curiosity to answer questions. Activities should therefore enable students to engage with real objects and with real problems. Programmes of teaching and learning need to 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.

Science should be experienced by students as aiming for understanding, not as a collection of facts and theories that have been proved to be correct. Scientific knowledge should be conveyed as a set of explanations for natural phenomena that are generally agreed to provide the best account of the available evidence. It should be recognised as the result of human endeavour involving creativity and imagination as well as careful collection and interpretation of data.

Principles applying to student assessment

> **Assessment has key roles in science education and should in all cases ultimately improve learning.**
>
> **The formative assessment of students' learning and the summative assessment of their progress must apply to all goals.**

Formative assessment should be used as an on-going part of teaching and learning to help students recognise the goals of an activity, judge the extent of their achievement of the goals and direct their effort effectively. Summative assessment, although more concerned with checking up and reporting on what has been learned, should be conducted in a way that supports further learning and avoids the negative impacts all too often associated with high stakes testing.

Since what is assessed and reported is assumed to reflect what it is important to learn, it is essential that this is not limited to what can be readily tested. A range of methods should be used to gather and interpret evidence of learning so that students are able to show what they can do in relation to all types of goals. It should also be recognised that for various unavoidable reasons (such as being able only ever to sample achievement and other inherent short-comings of assessment instruments), the assessment of learning outcomes is always an approximation.

Principles applying to teachers and schools

> **Programmes of study for students, and the initial training and professional development of teachers, should be consistent with the teaching and learning methods required to achieve the multiple goals of science education.**
>
> **In working towards these goals, schools' science programmes should promote cooperation among teachers and engagement with the community, including the involvement of scientists.**

Both initial and in-service teacher education should recognise that teachers as learners need to experience scientific activity and discourse at their own level. Courses should include opportunities to undertake different kinds of scientific inquiry, followed by reflection on the circumstances and the role of the teacher that supports understanding both *of* science and *about* science.

Opportunities should also be created for teachers to work together and with the local community and particularly with the scientific community. The challenge of improving science education requires the cooperation of educators and scientists. Teachers should have opportunities to improve their own understanding in science, for example, through continuing professional development in which scientists take part and by sharing their expertise with each other in conferences and courses. Information about the applications of science can often be supplied by those engaged in local industries or in science-based activities in the community. Enabling science students in higher education or professional 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 and at the same time learn about pedagogy that is effective in science education at all levels.

3 Revisiting big ideas: range, size and identification

Science is complex. How can we expect students even to begin to understand the vast array of ideas, theories and principles that seem to be necessary to grapple with this complexity? A clue to how this might be possible comes from listening to experts in science explaining to non-experts how the world works. They identify the (usually very few) key ideas which explain a phenomenon, cutting through the distracting detail. For example, a physicist can show how just two key ideas (Newton's second law and the universal law of gravitation) explain how satellites and space craft are kept moving round the Earth and enable us to calculate the velocities needed to keep these objects in orbit or bring them down to Earth. We are not suggesting the key ideas can be directly taught, or denying that building the relevant ideas involves bringing together many smaller ideas from a range of learning experiences. But we are convinced that ensuring that these learning experiences are linked to key ideas can provide the understanding that all students need to make sense of what they observe in the world. Moreover, as discussed earlier, this understanding can enable them to grasp what is involved in science-based decisions that affect their own and others' wellbeing.

Whether or not these potential benefits are realised will depend, of course, on the choice of ideas to be included. Two key decisions concern:

Range – whether to include scientific attitudes and dispositions towards science and what are variously called skills, practices, competences or capabilities as well as core scientific ideas.

Size – how broad a compass of phenomena the ideas should explain, recognising that the larger the idea, the more distant it is from particular phenomena and the more abstract it therefore appears to be.

Range

Science education is concerned with more than conceptual understanding, as expressed in the principles relating to aims (page 7). In addition to the ideas that explain what is going on in the world, science education has other aims, including developing:

- understanding of the nature of science
- the capabilities needed to engage in scientific activity
- scientific attitudes and informed attitudes towards science
- appreciation of the relationship of science to other subjects, particularly technology, engineering and mathematics.

Whilst acknowledging that science education should lead to these various outcomes, our decision to focus on big ideas *of* science and *about* science follows from our view that ideas play a central role in all aspects of science education. The development of understanding is a common factor in all science education activities. Science inquiry capabilities, or practices, and scientific attitudes and dispositions are developed by engaging in activities whose content involves science understanding; otherwise the activities can hardly be called scientific. Although we may emphasise and reinforce behaviours relating to, for example, cautious attitudes to interpreting data, or what is needed to plan a scientific investigation, the activity will also relate to one or more scientific ideas, for these attributes are not developed in isolation from scientific content. This argument does not negate the value of establishing lists of attitudes and abilities and explicitly working towards them at the same time as developing some conceptual understanding, but it reflects the principle that all science activities should deepen understanding of scientific ideas as well as having other possible aims.

Understanding the nature of science

We also want learners to understand the processes of scientific activity as well as the ideas to which it leads, that is, to know how the ideas that explain things in the world around have been arrived at not just what these ideas are. Indeed, it is hard to envisage separating knowledge about scientific activity from knowledge of scientific ideas. Without knowing how ideas were developed, learning science would require blind acceptance of many ideas about the natural world that appear to run counter to common sense. In a world increasingly dependent on the applications of science, people may feel powerless without some understanding of how to evaluate the quality of the information on which explanations are based. In science this evaluation concerns the methods used in collecting, analysing and interpreting data to test theories. 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.

Capacity to engage in scientific inquiry

Participation in scientific inquiry enables students to develop ideas about science and how ideas are developed through scientific activity. The key characteristic of such activity is an attempt to answer a question to which students don't know the answer or to explain something they don't understand. These may be questions raised by students but, since it is not realistic for all students always to be working on their own questions, it is part of the skill of teacher to introduce questions in a way that students identify them as their own. The answer to some questions can be found by first hand investigation, but for others information is needed from secondary sources. In either case the important feature is that evidence is used to test ideas and so the understanding that results will depend on what evidence is collected and how it is interpreted. Therefore, capabilities involved in conducting scientific inquiry have a key role in the development of ideas and the pedagogy that supports the development of big ideas must also promote the development of competence and confidence in inquiry. We return to this in Section 5.

The STEM context

The question about the relationship between science, technology, engineering and mathematics (STEM subjects) arises because understanding situations in daily life often involves combinations of these subjects; indeed much of what is referred to as 'science' in everyday life is better described as technology or engineering. Greater integration of STEM in educational programmes would afford opportunities for a better match of teaching and learning to practices in the work place and research settings and would be more likely to capture students' interest and engagement. A further argument for some degree of integration follows from the cognitive research that suggests connected knowledge is more readily applied in new situations than separate pieces of knowledge. However, what little research there is on the effects of integrating science with other subjects suggests that, at school level, it can be counter-productive to attempt to make connections if the ideas in each domain have not been securely learned. Rather than trying to teach the STEM subjects in an integrated manner, the advantages of bringing them together would be better secured by curriculum planning that coordinates related themes and topics.

Size

The issue of making connections across domains also arises in the context of addressing the question: how big should big ideas be? We identify big ideas of science as ideas that can be used to explain and make predictions about a range of related phenomena in the natural world. Explanatory ideas can come in different 'sizes': for any idea that applies to a few phenomena there is generally a bigger one applying to a larger number of related phenomena and which, in turn, can be subsumed into an even bigger, more comprehensive idea. For example, the phenomenon of one substance dissolving in another, such as sugar dissolving in water, is 'explained' by young children in terms of the sugar having disappeared. This naïve idea soon has to be adapted to account for the evidence that the sugar is still there in the water and then becomes 'bigger' to explain why some things do not dissolve in water and some colour the water but cannot otherwise be seen. Then, the idea of dissolving needs to be enlarged further to apply to other liquids and solids. This explanation might then be connected with how other phenomena are explained in terms of interactions at molecular levels.

The process of connecting ideas together to form bigger ones could continue in theory until there is a very small number of overarching concepts or even a single one that explains everything. Such ideas would necessarily be highly abstract, distant from actual experiences, and less useful for explaining these experiences than ideas that are more obviously linked to particular events and phenomena. They do not merely cut across subject discipline boundaries, as do ideas described as interdisciplinary, but completely obscure discipline boundaries and are better described as transdisciplinary. They include ideas such as system, symmetry, causality, form and function, and pattern.

Our decision to position big ideas at the interdisciplinary level, below the level of overarching transdisciplinary concepts, was taken by considering the needs of learners and their teachers. Discussing transdisciplinary ideas may be appropriate for the most able 18 year olds but otherwise is more appropriate for undergraduates and beyond. For the learner at school, who may or may not be embarking on a science-based career, the rather less general ideas with more obvious links to their experience 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 difference between a statement of goals and how these goals are best achieved. Further breakdown into a range of smaller ideas is, of course, possible but risks losing the connections between the smaller ideas that enable them to merge into a coherent big idea.

Identifying big ideas

The approach to science education of working towards development of big ideas has been widely accepted, and indeed welcomed, in principle. In order to decide what changes, if any, were necessary in the ideas published in *Principles and Big Ideas of Science Education* we first reviewed the selection criteria that had been used. We concluded that they continue to apply, that is, 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, such as the use of energy, involved in making decisions that affect learners' own and others' health and wellbeing and the environment
- lead to 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, inspiration from the study of nature and the impacts of human activity on the environment.

Feedback on the resulting selection of big ideas has not pointed to a need for major changes but rather that it has stood the test of informal peer review. At the same time, it became clear that there is some way to go before the approach is manifested in classroom practice and teacher education. More attention needs to be given to how to work with big ideas in practice and the implications for curriculum content, pedagogy and student assessment.

Consequently, even though we recognise that a different selection of ideas could be proposed, it was apparent that changes to the ideas at this stage, when they are beginning to be used, would not be helpful. Moreover, although not identical with the way in which ideas are presented in recently published curriculum frameworks, there are close similarities in the goals implicit in the curricula across many countries. For these reasons, having revisited the criteria used in selecting ideas and reviewed alternatives, we decided against making more than small changes of wording in the ideas identified and confirmed the selection of ten ideas of science and four ideas about science as before.

The following list gives the brief summaries of the ideas that all students should have had opportunity to learn by the end of compulsory education. In Section 4 these ideas are expressed more fully in narrative form describing the progression towards them over the years of schooling.

Ideas of science

1 **All matter in the Universe is made of very small particles**

Atoms are the building blocks of all matter, living and non-living. The behaviour and arrangement of the atoms explains the properties of different materials. In chemical reactions atoms are rearranged 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**

All objects have an effect on other objects without being in contact with them. In some cases the effect travels out from the source to the receiver in the form of radiation (e.g. visible light). In other cases action at a distance is explained in terms of the existence of a field of influence between objects, such as a magnetic, electric or gravitational field. 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.

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

A force acting on an object is not seen directly but is detected by its effect on the object's motion or shape. If an object is not moving the forces acting on it are equal in size and opposite in direction, balancing each other. Since gravity affects all objects on Earth there is always another force opposing gravity when an object is at rest. Unbalanced forces cause change in movement in the direction of the net force. When opposing forces acting on an object are not in the same line they cause the object to turn or twist. This effect is used in some simple machines.

4 **The total amount of energy in the Universe is always the same but can be transferred from one energy store to another during an event**

Many processes or events involve changes and require an energy source to make them happen. Energy can be transferred from one body or group of bodies to another in various ways. In these processes some energy becomes less easy to use. Energy cannot be created or destroyed. Once energy has been released by burning a fossil fuel with oxygen, some of it is no longer available in a form that is as convenient to use.

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

Radiation from the Sun heats the Earth's surface and causes convection currents in the air and oceans, creating climates. Below the surface heat from the Earth's interior causes movement in the molten rock. This in turn leads to movement of the plates which form the Earth's crust, creating volcanoes and earthquakes. 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 billions 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, gas and dust, one of many billions in the Universe, enormous distances apart. Many stars appear to have planets.

7 Organisms are organised on a cellular basis and have a finite life span

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 often depend on, or compete with, other organisms

Food provides materials and energy for organisms to carry out the basic functions of life and to grow. Green plants and some 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 as their source of energy. In any ecosystem there is competition among species for the energy resources 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. 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 resulting from natural diversity within a species lead to the selection of those individuals best suited to survive under certain conditions. Species not able to respond sufficiently to changes in their environment become extinct.

Ideas about science

11 Science is about finding the cause or cause of phenomena in the natural world

Science is a search to explain and understand phenomena in the natural world. There is no single scientific method for doing this; the diversity of natural phenomena requires a diversity of methods and instruments to generate and test scientific explanations. Often an explanation is in terms of the factors that have to be present for an event to take place as shown by evidence from observations and experiments. In other cases supporting evidence is based on correlations revealed by patterns in systematic observation.

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

A scientific theory or model representing relationships between variables of a natural phenomenon 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.

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

The use of scientific ideas in engineering and technologies has made considerable changes in many aspects of human activity. Advances in technologies enable further scientific activity; in turn this increases understanding of 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 cannot be addressed using scientific knowledge alone. Ethical and moral judgments may be needed, based on such considerations as justice or equity, human safety, and impacts on people and the environment.

4 Progression in developing big ideas

The development of understanding of big ideas in science is a gradual and progressive process continuing throughout formal education and beyond. It starts from the small, local and context-specific ideas that are formed through the study of particular phenomena. It involves both inductive and deductive thinking. Noticing patterns in observations may provoke questions about what is happening, but possible answers to these questions come from hypotheses drawn from previous experience, often involving a creative leap that connects previous to new observations. As learners use ideas from one event in explaining a related one their ideas become more useful in providing explanations that apply in several contexts. As ideas become less context-dependent they necessarily become more abstract.

For each individual learner there is a progression from initial ideas specific to and formed from their early experiences to more powerful ideas that explain a wider range of related phenomena. There is a huge amount of research into students' own ideas which shows that by the time they enter school they have formed ideas about aspects of the world and that many of their initial ideas are unlikely to be in line with scientific understanding. The path to more scientific ideas is unlikely to be the same for every individual since it depends on their experiences and on how they are helped to make sense of them. A description of progression – how ideas typically change over time – is important to inform curriculum development and the use of assessment both to help and to record learning. Most of all, however, it is important for teachers to see the connection between the learning experiences at various points in schooling and the overall aim of understanding big ideas.

Conceptions of progression

How are we to describe the progression of ideas from those that students form from their earliest years and bring to school to the grasp of big ideas we want them to have when they emerge from school? We found three main models of progression in ideas in the different ways in which learning goals are set out in curriculum frameworks.

The first, commonly applied, implicitly identifies progression with climbing a ladder, where each step has to be completed before the next step can be taken. What is needed to complete each step is set out as learning targets. The size of the step varies in different models; it can be a year or several years or stages. This approach gives the impression of a fixed linear development with progression seen as a series of separate stages each with its own end-point but not necessarily linked to the understanding of the overall big ideas. If this happens then the purpose and relevance of their science experiences may not be conveyed to students.

The second model is to describe only the overall end point, which can be reached in a variety of ways, rather as the pieces of a jigsaw can be put together in any order. This has disadvantages in providing too little guidance to teachers and other curriculum developers in deciding appropriate learning experiences.

The third model breaks overall goals into several strands. Ideas within each strand are gradually developed over time, often through a spiral curriculum. However, there is a risk of losing sight of connections between ideas in different strands that link them together in bigger ideas.

Each model has advantages and disadvantages and something of each is probably needed since the nature and breadth of experiences required to develop them varies for different ideas. For instance, in some cases students' own ideas lead them to different ideas for explaining essentially the same phenomenon encountered in different contexts. (For example, while they may explain that exposure to air and sunshine helps wet clothes to dry, they explain the disappearance of puddles in the road as the water leaking through the ground).The help they need is in making connections to see that a more scientific idea applies in each case (jigsaw). In other cases, students' ideas are based on limited experience ('all wood floats') and this has to be extended in order to lead to a more widely applicable idea (spiral). Again, students' reasoning is likely to be limited so that they may take notice only of evidence that confirms 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).

Describing progression towards the big ideas

Our approach is to provide a description – a narrative – of how ideas change from the small ideas, to the big ones identified in section 3. The narrative fills in some ideas that are formed in the progress from the beginning ideas to the broad, more abstract ideas that enable understanding of objects, phenomena and relationships in the natural world (ideas 1-10). We provide the same kind of description of how these understandings are achieved, that is, ideas about science (ideas 11-14).

Under each heading, where applicable, we begin with the small and contextualised ideas that children in the primary or elementary 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 phenomena. 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.

We have used a side bar to indicate the general range of ideas appropriate for different stages of schooling. Because there is so much variety in the way that phases of education are described in different countries we have labelled them in terms of ages, but using deliberately overlapping ranges since we do not intend to identify hard boundaries between what is appropriate at various ages. It is important to allow for diversity in the paths of cognitive development of individual students. What is important is the general direction of progress towards useful explanatory frameworks built on sound understanding at each stage. The ideas developed at all stages should be seen as contributing to this ongoing development. At each stage the aim is to move a little further towards a big idea, not to try to forge a link between every activity and the most sophisticated form of the idea. How far students can move in this direction at any time depends on a number of contextual variables, not least the pedagogy they experience, as discussed in Section 5.

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

Atoms are the building blocks of all matter, living and non-living. The behaviour and arrangement of the atoms explains the properties of different materials. In chemical reactions, atoms are rearranged 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.

5-7

All the 'stuff' encountered in everyday life, including air, water and different kinds of solid substances, is called matter because it has mass, and therefore weight on Earth, and takes up space. Different materials are recognisable by their properties, some of which are used to classify them as being in the solid, liquid or gas state.

7-11

When some substances are combined they form a new substance (or substances) with properties that are different from the original ones. Other substance simply mix without changing permanently and can often be separated again. At room temperature, some substances are in the solid state, some in the liquid state and some in the gas state. The state of many substances can be changed by heating or cooling them. The amount of matter does not change when a solid melts or a liquid evaporates.

11-14

If a substance could be divided into smaller and smaller pieces it would be found to be made of very, very small particles, smaller than can be seen even with a microscope. These particles are not in a substance; they are the substance. All the particles of a particular substance are the same and different from those of other substances. 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 differences between substances in the solid, liquid or gas state can be explained in terms of the speed and range 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 has to be transferred to the substance to separate the particles , for example in going from the solid to the liquid state or from the liquid to the gas state. This is why substances have different melting and boiling points.

All materials, anywhere in the universe, living and non-living, are made of a very large numbers of basic 'building blocks' called atoms, of which there are about 100 different kinds. Substances made of only one kind of atom are called elements. Atoms of different elements can combine 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.

14-17

Atoms themselves have an internal structure, consisting of a heavy nucleus, made of protons and neutrons, surrounded by light 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. The behaviour of matter at the scale of nuclei, atoms and molecules is different from that observed at the scale of ordinary experience.

2 Objects can affect other objects at a distance

All objects have an effect on other objects without being in contact with them. In some cases the effect travels out from the source to the receiver in the form of radiation (e.g. visible light). In other cases action at a distance is explained in terms of the existence of a field of influence, such as a magnetic, electric or gravitational field. Gravity is a universal 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.

7-11

Objects can have an effect on other objects even when they are not in contact with them. For instance, light, both from close sources such as light bulbs or flames and from the Sun and other stars very long distances away, is seen because it affects the objects it reaches, including our eyes. These sources give out light, which travels from them in various directions and is detected when it reaches and enters our eyes. Objects 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 enter our ears. Other examples of objects affecting other objects without touching them are the interactions between magnets or electric charges and the effect of gravity that makes things falls to the Earth.

11-14

Gravity is the universal attraction between all objects, however large or small, although it is only apparent when one of the objects is very large. This gravitational attraction keeps the planets in orbit round the Sun, the Moon round the Earth and their moons round other planets. On the Earth it results in everything being pulled down towards the centre of the Earth. We call this downward attraction the weight of an object. The object pulls the Earth as much as the Earth pulls the object, but because the Earth's mass is much bigger, we observe the resulting motion of the object, not of the Earth. The effect 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 weighs 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 the Earth gives rise to tides.

14-17

Visible light is one example of radiation, which spreads out in a way resembling how waves spread across water. Other kinds of radiation 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 (vacuum). 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, in a solid, liquid or gas state, between the source and the receiver for the vibrations to travel through.

When radiation hits another object, it may be reflected, 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 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 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 – attraction or repulsion. Gravity, electric and magnetic interactions can be described in terms of fields.

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

A force acting on an object is not perceived directly but is detected by its effect on the object's motion or shape. If an object is not moving the forces acting on it are equal in size and opposite in direction, balancing each other. Since gravity affects all objects on Earth there is always another force opposing gravity when an object is at rest. Unbalanced forces cause change in movement in the direction of the net force. When opposing forces acting on an object are not in the same line they cause the object to turn or twist. This effect is used in some simple machines.

5-7

Forces can push, pull or twist objects, making them change their motion or shape. Forces act in particular directions. Equal forces acting in opposite directions in the same line cancel each other and are described as being in balance. The movement of objects is changed if the forces acting on them are not in balance.

7-11

The speed of a moving object is a measure of how far it would travel in a certain time. 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.

11-14

All objects on the Earth are affected by gravitational forces. 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 book with a force equal to the downward force of gravity. An object floating in a liquid or in air does not move because there is an upward force balancing the downward force of gravity. The upward force is equal to the weight of the fluid displaced so heavy objects can float if they are hollowed out to displace a large weight of water.

14-17

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 (acceleration) or slow it down (deceleration). 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 with its surroundings. 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. 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 turning effect of a force depends on its distance from the axis about which it turns. The further the distance from the turning point the less force is needed but the further it has to move. This has many applications in tools and machines where a small force acting over a large distance is used to produce a large force acting over a small distance.

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. The pressure in a fluid (liquid or gas) at particular point depends on the weight of fluid above that point, so air pressure on Earth decreases with increasing height above the ground and pressure in a liquid increases with depth.

4 The total amount of energy in the Universe is always the same but can transferred from one energy store to another during an event

Many processes or events involve changes and require an energy source to make them happen. Energy can be transferred from one body or group of bodies to another in various ways. In these processes some energy becomes less easy to use. Energy cannot be created or destroyed. Once energy has been released by burning a fossil fuel with oxygen, some of it is no longer in a form that is as convenient to use.

5-7

There are various ways of causing an event or bringing about change in objects or materials. Objects can be made to change their movement by pushing or pulling. Heating can cause change, as in cooking, melting solids or changing water to vapour. Electricity can make light bulbs glow. Wind can rotate the blades of wind turbines.

7-11

In all these changes, energy is transferred from one object, which is an energy source or resource, to another. Fuels such as oil, gas, coal and wood are energy resources. Some energy resources are renewable, such as those produced by wind, waves, sunlight and tides, others are non-renewable such as from burning fossil fuels with oxygen.

11-14

Objects can have stored energy (that is, the ability to make things change) 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. When it is released and falls, this energy is stored in its motion. When an object is heated it has more energy than when it is cold. An object at a higher temperature heats the surroundings or cooler objects in contact with it until they are all at the same temperature. How quickly this happens depends on the kind of material which is heated and on the materials between them (the extent to which they are thermal insulators or conductors). The chemicals in the cells of a battery store energy which is released when the battery is connected so that an electric current flows, transferring energy to other components in the circuit and on to the environment. Energy can be transferred by radiation, as sound in air or light in air or a vacuum.

Many processes and phenomena are described 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 energy being shared more widely, heating more atoms and molecules and spreading out by conduction or radiation. The process cannot be reversed and the energy of the random movement of particles cannot as easily be used. Thus some energy is dissipated.

14-17

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, heating the Earth and other planets. The mass of atoms is a form of stored energy, called nuclear energy. Radioactive atoms release this energy which may become 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. Fossil fuels, frequently used in power stations and generators, are a limited resource and their combustion contributes to global warming and climate change. Therefore other ways of generating electricity have to be sought, whilst reducing demand and 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

Radiation from the Sun heats the Earth's surface and causes convection currents in the air and oceans, creating climates. Below the surface heat from the Earth's interior causes movement in the molten rock. This in turn leads to movement in the plates which form the Earth's crust, creating volcanoes and earthquakes. The solid surface is constantly changing through the formation and weathering of rock.

5-7

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 and movement of the air. The temperature, pressure, direction, 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 weather a short time ahead. Long-term patterns in the weather are referred to as the climate of different parts of the world.

7-11

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 compositions and properties. The action of wind and water wears down rock gradually into smaller pieces – sand is made of small pieces of rock and silt of still smaller pieces. About two-thirds of the surface of the Earth is covered by liquid water, which is essential to life. Water is constantly recycled through processes involving evaporation from oceans and other surfaces, such as soil and plants, condensation in clouds and precipitation as rain, snow or hail.

11-14

The layer of air at the Earth's surface is transparent to most of the radiation coming from the Sun, which passes through. The radiation that is 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 that enables 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, keeping the Earth warm. This is called the greenhouse effect because it is similar to the way the inside of a greenhouse is heated by the Sun.

14-17

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 which absorbs this harmful radiation. The temperature at the Earth's surface results from a delicate balance, which can be upset by adding gases to the atmosphere. Human activities produce carbon dioxide and methane which increase the greenhouse effect and leads to global warming and climate change.

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 billions 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, gas and dust, one of many billions in the Universe, enormous distances apart. Many stars appear to have planets.

5-7

There are patterns in the position of the Sun seen at different times of the day and in the shape of the Moon from one night to another.

7-11

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. 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, giving rise to the seasons.

11-14

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 which appear fixed relative to each other. Exploring the solar system is possible with robotic missions, or by humans at shorter distances from the Earth.

14-17

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'. A meteor is a rock that is all burnt up on entering the atmosphere but if some of it reaches the Earth's surface it becomes a meteorite. Otherwise movements of object within the solar system are mostly regular and predictable. The same scientific laws – 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. Life has not (yet) been discovered anywhere outside Earth.

Our Sun is one of many stars that make up the Universe, essentially made of hydrogen. The source of energy that the Sun and all stars radiate comes from nuclear reactions in their central cores. The Sun is one of millions of stars that together make up a galaxy called the Milky Way. The next nearest star is much further away than the distance of the furthest planet, Neptune. The distances between and within galaxies are so great that they are measured in 'light years', the distance that light can travel in a year. There are billions of galaxies in the universe, almost unimaginably vast distances apart and perceived as moving rapidly away from each other. This apparent movement of galaxies indicates that the Universe is expanding from an event called a 'big bang', about 13.7 billion years ago.

7 Organisms are organised on a cellular basis and have a finite life span

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.

5-7

7-11

There is a wide variety of living things (organisms), including plants and animals. They 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. Although some do not appear to be active, all will at some stage carry out the life processes of respiration, reproduction, feeding, excretion, growth and developments and all will eventually die.

11-14

All living organisms are made of one or more cells, which can be seen only through a microscope. All the basic processes of life are the results of what happens inside cells. Cells divide to replace aging cells and to make more cells in growth and in reproduction. Food is the energy source they need in order to carry out these and other functions. Some cells in multi-cellular organisms, as well as carrying out the functions that all cells do, are specialised; for example, muscle, blood and nerve cells 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 such key functions as 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. Stem cells, which are not specialised, are capable of repairing tissues by being programmed for different functions. Cells function best in certain conditions. Both single cell and multi-cellular organisms have mechanisms to maintain temperature and acidity within certain limits that enable the organism to survive.

14-17

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. 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.

Given a suitable medium, cells from a variety of organisms can be grown *in situ*, that is, outside the organism. These cell cultures are used by scientists to investigate cell functions, and have medical implications such as the production of vaccines, screening of drugs, and in vitro fertilisation. Plant tissue culture is used widely in the plant sciences, forestry, and in horticulture.

Most cells are programmed for a limited number of cell divisions. Diseases, which may be caused by invading microorganisms, environmental conditions or defective cell programming, generally result in disturbed cell function. Organisms die if their cells are incapable of further division.

8 Organisms require a supply of energy and materials for which they often depend on, or compete with, other organisms

Food provides materials and energy for organisms to carry out the basic functions of life and to grow. Green plants and some 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 as their source of energy. In any ecosystem there is competition among species for the energy resources and the materials they need to live and reproduce.

5-7

All living things need food as their source of energy as well as air, water and certain temperature conditions. Plants containing chlorophyll can use sunlight to make the food they need and can store food that they do not immediately use. Animals need food that they can break down, 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.

7-11

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

11-14

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, (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 resources pass through the ecosystem. When food is used by organisms for life processes some energy is dissipated as heat but is replaced in the ecosystem by radiation from the Sun being used to produce plant food.

In any given ecosystem there is competition among species for the energy resources and the materials they need to live. The persistence of an ecosystem depends on the continued availability in the environment of these energy resources and materials. 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 changes to animal populations.

14-17

Human activity which controls the growth of certain plants and animals changes an ecosystem. Forestry which favours the growth of certain trees over others removes the food plants of certain animals and so reduces the diversity of species dependent on these plants and of other organisms in the food chain. Modern farming is designed to reduce biodiversity by creating conditions that are suited to particular animals and plants in order to feed the human population. The widespread use of pesticides to preserve one type of crop has widespread effects on pollinating insects on which many other plants depend. Human activity of this kind creates a simple and unnatural ecosystem which limits biodiversity and results in the loss of culturally valuable landscape and wildlife.

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

Genetic information in a cell is held in the chemical DNA. 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.

5-7

7-11

Living things produce offspring of the same kind, but 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.

11-14

Inside the nucleus of animal and plant cells are structures called chromosomes which hold large complex molecules of DNA. When cells divide the information that is needed to make more cells is in the form of a code represented in the way that the parts of the DNA molecule 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 thousand genes.

When a cell divides, as in the process of growth or replacement of dead cells, genetic information is copied so that each new cell carries a replica of the parent cell. Sometimes 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 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.

14-17

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.

The overall sequence of genes of an organism is known as its genome. 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 are beginning to help in curing disease.

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 resulting from natural diversity within a species lead to the selection of those individuals best suited to survive under certain conditions. Species not able to respond sufficiently to changes in their environment become extinct.

5-7

7-11

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 sparrow, and different kinds (species) within a family such as house sparrows, tree sparrows, and great sparrows. Organisms of the same species breed more of the same. Different species cannot interbreed to produce offspring that can reproduce. Although organisms of the same species are very similar they vary a little from each other. One of the results of sexual reproduction is that offspring are never exactly like their parents.

11-14

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 resources, those that are better adapted are more likely to survive and may pass on their adapted feature to their offspring. Those less suited to a particular environment are more likely to die before reproducing, so later generations will contain more of the better adapted individuals. This only applies to changes (mutations) in the reproductive cells; mutations in other cells are not passed on. Over time, these changes can accumulate to the point where the survivors have become a different species.

The natural selection of organisms with certain features that 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 unicellular.

14-17

When climatic, geological or population changes occur, the benefit of particular inherited features may be enhanced or diminished. The process of adaptation that occurs naturally and very slowly is speeded up by human intervention through the selection for breeding those animals or plants with the features that suit them for particular functions or environments.

Human activity can change the environment more quickly than organisms can respond through adaptation. Water, air and soil pollution as well as intensive farming 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 hundreds of times what is would be if there were no people. A reduction in the diversity of life can lead to significant ecosystem degradation and loss of ability to respond to changes in the environment.

Evolution of life on Earth is only a limited aspect of what is called 'cosmic evolution'. This refers to the gradual changes in the physical and chemical conditions of the galaxies, such as the appearance of the carbon atom, which has led to favourable conditions for the existence of life, at least on Earth.

11 Science is about finding the cause or causes of phenomena in the natural world

Science is a search to explain and understand phenomena in the natural world. There is no single scientific method for doing this; the diversity of natural phenomena requires a diversity of methods and instruments to generate and test scientific explanations. Often an explanation is in terms of the factors that have to be present for an event to take place as shown by evidence from observations and experiments. In other cases supporting evidence is based on correlations revealed by patterns in systematic observation.

7-11

Science is about finding explanations for why things happen as they do or why they take a particular form, assuming that every event or phenomenon 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 basis 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 a change and observe what happens. When this is done it is important to see that other things stay the same so that the result can only be the effect of changing one thing.

11-14

Careful and systematic observations and accurate descriptions of what is observed are fundamental to scientific investigation. What people expect to happen can influence what they observe, so it is good practice for observations to be made by several people independently and for results to be reported clearly enough to be checked by others.

Different kinds of natural phenomena are explained in different ways. In some cases a possible explanation (hypothesis) indicates the variable factor thought to cause a phenomenon. To test a hypothesis it is used to predict what will happen when the variable identified as a possible cause is changed and then see if what happens fits the prediction. If the outcome agrees with the prediction, and no other changes are found to produce the same result, then the factor is accepted as being the cause that explains the observation.

14-17

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 a hypothesis, 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 change in one factor is the cause of the change in the other because there could be some other factor (so far unidentified) that is causing both. 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 evidence available at a particular time

A scientific theory or model representing relationships between variables of a natural phenomenon 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.

5-7

Everyone can ask questions about things in the natural world and can do something to find answers that help explain what is happening.

7-11

In science explanations are sought through some kind of systematic inquiry that involves collecting data by observing or measuring features of the objects being studied or using data from other sources. Whether or not an effective 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.

11-14

To help in the process of explaining observations and what makes things happen, scientists create models to represent what they think may be happening. Sometimes these are physical models, such as an orrery – a model of the solar system where various objects are used to represent the Sun, Moon, Earth and other planets – or a ball and stick model of how atoms are thought to be arranged in a substance. Other models are theoretical, more abstract, such as in representing light as a wave motion, or representing relationships as mathematical formulae. Computer-based models enable phenomena to be simulated and variables easily changed to investigate their effect. 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. There may be 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.

14-17

Models provide ways of explaining phenomena in terms of relationships between parts of a system. They are developed through an iterative process of comparing what they predict with what is found in the real world. Model-based reasoning goes beyond what can be observed directly, whilst keeping the link with evidence by comparing what a model predicts with what can be observed.

Scientific explanations account for specific events or phenomena in terms of a theory or model. Explanations do not emerge self-evidently from data but are created in a process that often involves intuition, imagination and informed hypothesis. A scientific theory is a well-substantiated explanation of some aspect of the natural world, based on a body of facts that have been repeatedly confirmed through observation and experiment and so become well established.

If new data do not fit current ideas then the ideas have to be changed or replaced by alternative ideas. Although there is greater confidence in ideas or models that leads to predictions that are repeatedly and reliably confirmed by evidence – and so become regarded as facts – an explanation or theory can never be proved ‘correct’ because there is always the possibility of further data conflicting with it or because a new theory is found that also provides a good explanation. 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 engineering and technologies to create products

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 of the natural world. In some areas of human activity technology is ahead of scientific ideas, but in others scientific ideas precede technology.

5-7

Technologies have been created by people to provide the things they need or can use, such as food, tools, clothes, somewhere to live and ways of communicating. All around us are examples of how materials have been changed so that they can be used for certain purposes.

7-11

Technologies are developed using engineering, which involves identifying problems and using ideas of science and other ideas to design and develop the best possible solution. There are always different ways of approaching problems, so various possibilities need to be tried out. In order to decide which is the best solution it is necessary to be clear about what the result is intended to be and so how success is to be judged. For instance, a solution to the problem of being able to see the back of your head would be different if a criterion for success is to leave your hands free.

11-14

Designing a solution to a problem generally involves making a drawing or model. Physical, mathematical or computer models enable the effect of changes in materials or design to be tested and the solution improved. There are usually many factors to be considered in optimising a solution, such as cost, availability of materials and impact on users and on the environment, which may constrain choices.

14-17

Science, engineering and technology are closely inter-connected. The application of science in making new materials is an example of how scientific knowledge has led advances in technology and provided engineers with a wider choice in designing constructions. 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, technology aids scientific advances which in turn can be used in designing and making things for people to use. Often in the past technological products have been developed empirically in advance of scientific ideas, whilst today usually scientific understanding come first or at the same time. The application of science in designing and making new tools and machines has made mass production possible so more people have access to a range of commodities.

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, presenting a waste disposal problem when discarded. Some technological devices such as mobile telephones and computers use metals that exist in the Earth only in small quantities and could soon 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 engineers need to collaborate in understanding the problem and in finding solutions.

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 cannot be addressed using scientific knowledge alone. Ethical and moral judgments may be needed, based on such considerations as justice or equity, human safety and impacts on people and the environment.

7-11

The understanding of the natural world that is developed through science enables us to explain how some things work or phenomena occur. This understanding can often be applied to change or make things to help solve human problems. Whilst such technological solutions have improved the lives and health of many people in countries across the world, it has to be recognised that they may use materials from the natural world which may be in short supply or may be detrimental to the environment.

11-14

There are generally both positive and negative consequences of the applications of science. Some negative impacts can be anticipated but others emerge from experience. Clean water, adequate food and improved medicines have increased human life expectancy but 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 and engineering 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. If the detrimental effects are known, the trade-off between the advantages and the disadvantages of the application of science needs careful consideration.

14-17

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 but decisions about action will be based on values and competing needs, not on the scientific evidence alone. Thus, when designing a new system or product engineers have to take account of ethical values, political and economic realities as well as science and technology.

Scientific understanding can help to identify implications of certain applications but decisions about whether certain actions should be taken will require ethical and moral judgements which are not provided by knowledge of science. There is an important difference between the understanding that science provides about, for example, the need to preserve biodiversity, the factors leading to climate change and the adverse effects of harmful substances and lifestyles, and the actions that may or may not be taken in relation to these issues. Opinions may vary about what action to take but arguments based on scientific evidence should not be a matter of opinion.

5 Working with big ideas in mind

For many years there have been repeated and widespread calls for greater depth and less uncoordinated breadth in the goals of science education. The publication of *Principles and Big Ideas of Science Education* responded to this challenge by identifying a relatively small number of ideas that science education should aim for all students to develop. The feedback we received – from the many countries where the publication has been translated and used – gave no indication that it was necessary to make any more than minor corrections and changes in the descriptions of the ideas identified.

What is needed, however, is more experience and discussion of the implications in practice of working with these big ideas in mind. In particular, what difference does it make to decisions about the key elements of students' learning experiences: choice of curriculum content, pedagogy and student assessment? In this section we attempt to answer these questions.

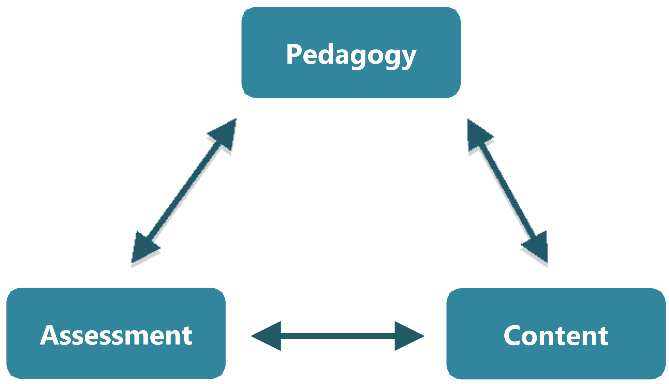

Figure 1:
Interactions among aspects of students' experience

The three aspects of students' experience represented in Figure 1 are not independent of one another. As indicated by the arrows, changes in one affect the others. These interactions are important, since it is no use suggesting that the content should be focused on big ideas if the assessment requires memorising multiple facts or if the pedagogy does not forge links that are necessary to form these big ideas. It is no use advocating the use of inquiry-based teaching if there is an overbearing summative assessment system (whether by external testing or teachers' judgements) or a curriculum overcrowded with content. Nor can we expect students to develop responsibility for their own continued learning if teaching does not allow time for reflection and room for creativity, or hope for positive attitudes towards science if the curriculum content seems to students to be remote from their interests and experience.

Opportunities for all students

As we consider the opportunities to learn provided through the curriculum content, pedagogy and assessment, it is important to keep in mind the key principle of equity (page 7), that all students equally need these opportunities as preparation for life in today's complex world. The conviction that all students can learn is underpinned by research, yet marked and persistent differences in achievement, associated with gender, cultural background and socioeconomic status are found in very many countries. Of the numerous factors involved in accounting for these differences in relation to science, opportunities to learn, both in school and out of school, are of paramount concern. Although increasingly students learn outside schools, which are no longer the main source of knowledge, schools are still key sources of formal learning opportunities. However, students from advantaged homes and neighbourhoods are far more likely to attend schools with good provision for science teaching, to complete their secondary education and to continue their education thereafter, than are students from deprived neighbourhoods.

Schools with a high proportion of students from disadvantaged backgrounds are very likely to give priority to making up their students' deficiencies in language and mathematics over all other subjects, including science. In addition, they are often ill-equipped in terms of teaching expertise and resources for teaching science. Consequently their students miss out on the early experiences that are the foundation for developing understanding of scientific ideas and practices and the benefits that follow from it.

The identification of the problems suggests solutions. Schools need the teachers, the support, equipment, and guidance that are necessary to ensure that students of all backgrounds have equal opportunities to learn. This may mean reallocation of human and material resources. It may also mean guidance in ensuring that assessment is used to help learning and that assessment methods do not disadvantage students with poor linguistic skills or where the language of the home is different from the language of instruction. But just as important is guidance in using diversity among students to advantage, in accordance with the principles applying to the selection of activities (page 8), so that the everyday experiences and ideas that all students bring to school are the basis for their development of scientific ideas

Curriculum content

By curriculum content we mean the particular topic or subject matter studied as a vehicle for students to achieve the ideas, skills and attitudes set out in a formal programme of study. Since there are numerous settings for the development of ideas about, for instance, forces and movement, food chains, or the insulating properties of different materials, there has to be some way of choosing among possible topics and activities. The principles in Section 2 imply some criteria for selection: activities should promote enjoyment of scientific activity; sustain curiosity; be seen by students as interesting and relevant to their lives; and of course develop scientific understanding, capabilities and attitudes. Further, a central part of the reason for identifying big ideas is for students to experience how science enables us to understand how the world works.

Using content from the world around

Teachers generally instinctively recognise the need to capture the interest of their students and that this is best attempted through selecting content relating to a real or possible but hypothetical experience. Teachers of young children are expert at creating a story or an imagined situation as a setting for investigations – building a model house out of shoe boxes in the classroom as a context for exploring different materials that are used in real constructions, or imagining how to keep warm on a cold and windy mountain as a reason for testing the insulating properties of different fabrics. For older students the pretence can be supplemented by real experience, through visits to power stations, water-treatment plants, recycling centres, etc. Not only can such visits motivate interest in how these essential services are provided, but they give students opportunity to see how science is applied in these processes.

Real world topics provide interest and motivation. The motivating link is important, particularly in an age where children have instant access to entertainment not only through television but also at any time on their mobile devices. But events and phenomena in the world around are usually too complex for students to be able to understand how they work by directly interacting with the actual events or phenomena. Although using real world contexts has many advantages – and there are certain phenomena that need to be studied *in situ* precisely because of the complexity – it can also be confusing. The considerable detail of actual events can obscure the characteristics that need to be identified in order to develop ideas that transfer to other settings.

Learners need help in giving attention to the critical (as opposed to the irrelevant) features of a complex problem and it should not be assumed that they are able to identify underlying and applicable relationships for themselves. So, to avoid confusion of working only in the field, we take the essence of the problem into the classroom or laboratory where ideas can be more directly tested and developed. Whether the context that motivates engagement is a story or a visit, the science is learned in a simplified version of reality in the classroom or laboratory where conditions can be controlled and variables measured.

In this process it is important not to lose the link to things in the world around. Unless the crucial link back into the 'real' setting is maintained, there is a risk of the relevance of classroom-based activities being forgotten. So there is a need for a balance between the richness and cognitive demands of too much information associated with real world contexts and study of specific selected aspects that help to make connections between different events and phenomena. Also important is regular discussion of how the findings of classroom inquiries are connected to the initial motivating context. Most significant for the development of bigger ideas are challenges to apply emerging ideas to new situations and to make connections with the ideas used to explain them.

Ways of engaging with content

There are some topics that are best addressed through investigation and inquiry whilst others are more appropriately presented as an account of a scientific discovery or discussion of experiments or findings of current topical interest. All of these should be included in the selection of content linked to the big ideas. It is important for students to have opportunities for discussing how some ideas have changed in the history of science and the reasons for these changes. Extending such discussion to students' own investigations helps students to recognise the role of evidence in the development of understanding, advancing their progress towards big ideas about the nature of science and its applications. This is further helped by discussion of how applications of science have led to developments in, for instance, medicine, communications, and travel. Topics such as these generally engage students' interest and are key sources of motivation to develop their ideas about events and phenomena in the world around.

Progression in engaging with content

It is possible to study the same events, habitats and phenomena at different times across the years of schooling as long as the ways in which the content is investigated take account of students' progression over time in the development of relevant ideas. As noted in Section 4, the pace of this progression will vary from student to student according to their previous 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:

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

The references here to increasing use of quantification of observations and models of relationships highlight the important role that mathematics takes in developing ideas in science through inquiry. Mathematics helps students to go beyond description in words. Organising data through representation in graphs, charts and tables helps students to notice patterns and make connections that develop their thinking about associations between variables, and to formulate hypotheses about causes that can be tested. Analysing data statistically enables students to make inferences about the probability of relationships and predictions. There is mutual benefit in coordinating science and mathematics education; mathematical tools help understanding in science and, at the same time, using data from science investigations helps in the developing appreciation of the range and application of these tools.

Pedagogy

When trying to make sense of new experience, whether within the classroom or outside, learners start from the ideas they already have, as indeed do scientists when they are trying to explain phenomena and develop their understanding of how things behave in the world around. In science, understanding of the natural and made world is developed through seeking answers to questions by collecting data, reasoning and reviewing evidence in the light of what is found and what is already known, drawing conclusions and communicating results. The source of data may be the direct manipulation of materials, observation of phenomena or use of secondary sources including books, the internet, the media and people. The interpretation of the data to provide evidence to test ideas may involve debate with other students and the 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.

Developing ideas through inquiry

The process of developing ideas in this way is described as one of inquiry – using scientific investigation and the capabilities used by scientists to develop understanding of the world around. What it involves in practice is represented in a simplified schematic model in Figure 2.

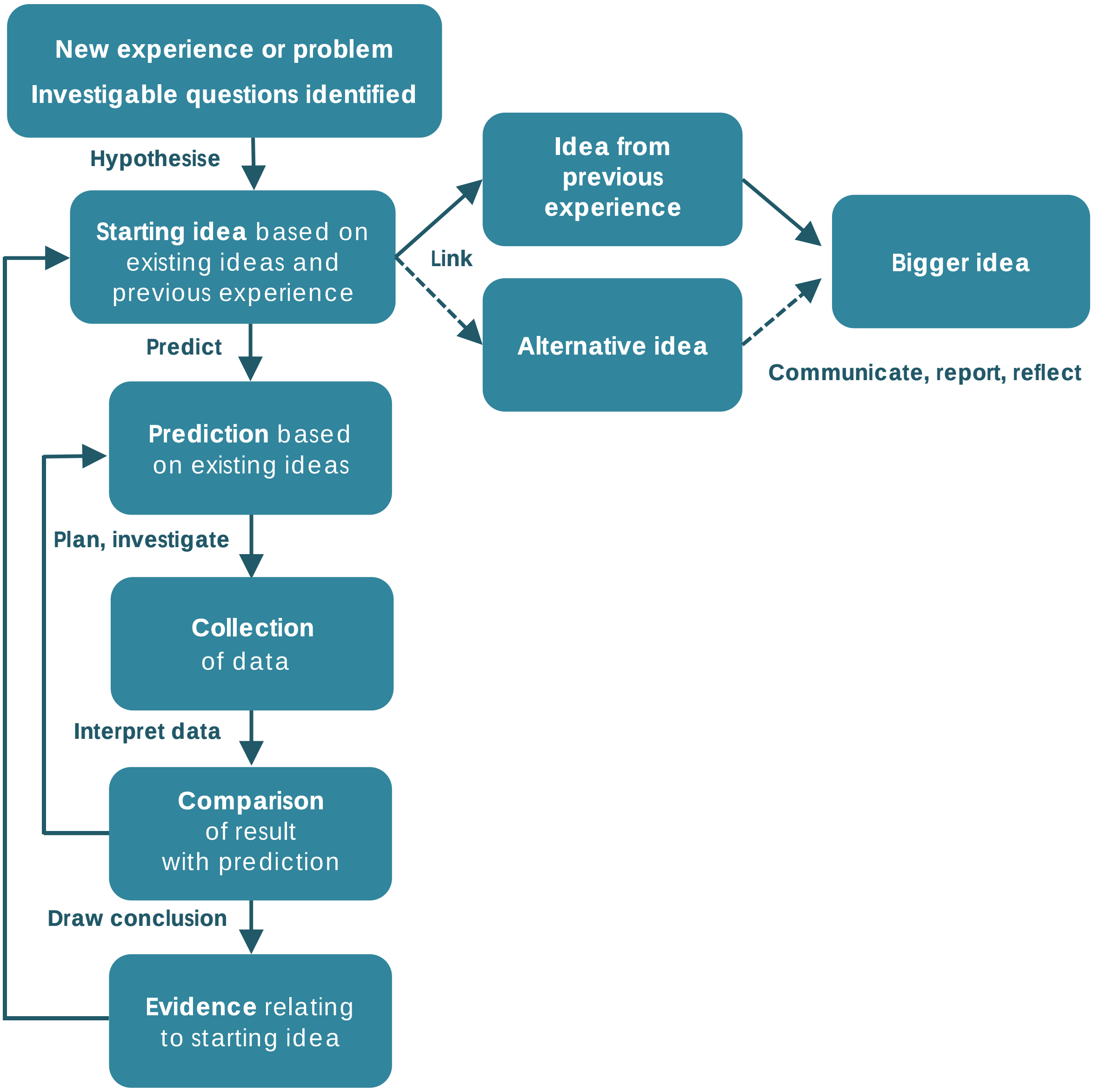

Figure 2:
A model of learning through inquiry

Inquiry begins with a new experience that raises a question about how it can be explained. Initial exploration of the new experience reveals features that relate to existing ideas that may lead to a possible explanation. There may be several relevant ideas providing possible explanations (or hypotheses) that need to be tested to find which, if any, provides an acceptable answer. In each case the test is whether there is evidence to support a prediction based on it. Evidence is gathered through planning and conducting an investigation, which may involve collecting and interpreting new data, systematic observation or consulting secondary sources. There may be more than one prediction to be tested and so the sequence of prediction, planning and interpretation may need to be repeated. The conclusion drawn from the new data shows whether there is evidence to support the possible explanation and the idea on which it is based. If there is, then the idea becomes '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 that idea. It is important that students share with others the whole process of activities and reasoning so that all benefit from critical discussion and learn from what doesn't work as well as what does.

Developing inquiry capabilities

The arrows in Figure 2 are labelled with the actions needed to move from one box to the next. The results of the inquiry will depend on how these actions are carried out, that is, how well students make a prediction, plan an investigation to test it, how they interpret data and draw conclusions. The development of scientific ideas is dependent on the collection and interpretation of data being carried out with scientific rigour. Otherwise ideas may be accepted that ought to be rejected and students' own unscientific ideas persist. It follows that a key part of the pedagogy required to develop understanding is to help students to develop the capabilities needed in scientific investigation, in accordance with the principles on page 7. This is best done in the context of inquiries that lead to some understanding of the world around, where the reasons for taking certain actions can be seen. Thus the value of inquiry goes beyond finding an answer to a particular question; it contributes both to the understanding of the big ideas that apply beyond the specific event or phenomenon being studied and to the development of capabilities and dispositions that enable further learning, such as confidence in raising questioning and in seeking answers to them, learning in collaboration with others and openness to new ideas.

Introducing alternative ideas

The ideas used by students in trying to explain events are not always – in fact, not often – ones that will survive being tested and so 'grow' into a more scientific ideas. More often, an alternative more scientific idea needs to be proposed. For example, students may explain how they see an object that is not a source of light as being a result of their eye directing a beam towards it. Testing this idea (e.g. by trying to see the object in the dark) shows that it doesn't provide an adequate explanation. There is then an important role for the teacher in providing access to alternative ideas and support in testing them.

Alternative ideas may come from other students, from information sources or from the teacher suggesting analogies or links to experience that student may not have thought of. Testing these alternative ideas that are not the students' own requires scaffolding – giving support for trying an idea without urging it as the 'right answer' by suggesting, for example, '*what if …?*' or '*suppose that …?*' or '*what would we expect if* … ?' With this support students gather evidence that enables them to decide whether an idea that is new to them provides a satisfactory explanation. If it does, then the introduced idea becomes 'bigger' because it then explains more than before and becomes part of students' developing understanding.

Inquiry and practical work

Sometimes inquiry-based science is equated with 'practical work' or 'hands-on' activities. This is too limited a view of inquiry in science. Of course, a good deal of inquiry *does* involve working with materials and equipment to find evidence of what happens when certain things are changed and to test a theory of why this happens. Direct experience enables students to see for themselves whether their ideas and explanations work. However, teachers need to beware of pseudo-inquiry, where there is plenty of practical activity – observing, measuring and recording – but a lack of involvement of the students in making sense of phenomena or events in the natural world. This may be because the teacher is doing the interpretation for the students, or it may be that the students are following precise instructions with little thinking about the purpose of what they are doing. Evaluation of teaching, as suggested in Section 6, may help to identify the reason in particular cases.

Inquiry in context

As we noted in Section 3, inquiry means that students are developing their understanding through their own investigation of questions to which they do not know the answer and want to find an answer. The questions may be ones that they have raised for themselves, or ones introduced by the teacher in a way that enables students to identify as their own. A few investigations where student do the thinking, starting from a question that they have identified as important to them, will be far more helpful for the development of big ideas than a larger number of routine exercises.

Inquiry will not be the only form of pedagogy that students encounter in their science education, for there are some things to be learned such as skills of using equipment, names, conventions and symbols which are best taught directly. Also, in the secondary school, students need to be introduced to complex and abstract ideas that are not accessible to them through inquiry alone. Indeed, at all stages there will be occasions where inquiry contributes to making sense of experience without being the sole approach used. Inquiry will enable students to understand how certain ideas explain phenomena but will not, of itself, be the source of these ideas, since ideas do not emerge from observations by a simple process of induction. Thus teachers' ability to introduce scientific ideas at an appropriate level, and to scaffold their use by students, is a central part of inquiry-based science education. This means that teachers need a good understanding of the big ideas and the path of progression towards them.

Assessment

In the context of building big ideas, assessment of students' learning serves two important purposes:

- to provide feedback that helps teachers to regulate teaching and students to direct their efforts more effectively (formative assessment)
- to keep track of students' progress towards the various goals of science education (summative assessment).

It is important to emphasise that these are not two different kinds of assessment, but rather two different and equally important purposes for which assessment is used. It is the use made of the evidence of learning that makes assessment data formative or summative, not the type of evidence and not only when or how it is gathered.

Formative assessment

The formative use of assessment is a continuing cyclical process in which information about students' ideas and capabilities informs on-going teaching and facilitates active engagement of students in learning. It is integral to teaching and a feature of effective practice in all subject domains. Formative assessment involves teacher and students gathering and using evidence to make decisions about the next steps in learning and how to take them. The next steps are those that take the student towards particular lesson goals. An important part of formative assessment is for teachers to share these goals with students so that they realise the purpose of their work in terms of what they can learn through it. Making explicit to students the expectations of quality that are used in judging their work also helps them to direct their efforts effectively. At the same time the teacher recognises how these short-term lesson goals take students towards longer-term goals, including understanding big ideas.

Feedback, both to students and to teachers, has a key role in formative assessment, since it is the means of using evidence of current learning to help further learning. Feedback from teacher to students should give students information they can use to take their learning forward. Research into the content and form of feedback to students indicates that this is most effective when it provides specific comments about how to proceed rather than judgemental comments, or marks or grades that only indicate how good or otherwise the work is judged to be. Feedback into teaching is the mechanism by which teachers can use observations of students and their work to adjust the challenges they provide for students. Judging students' ability to take certain steps facilitates the regulation of teaching so that the demands of activities are neither too great – making success out of reach – nor too simple to be engaging.

So, what is required of teachers in using formative assessment for developing big ideas? Evidence of students' current ideas can be gathered by asking questions that encourage students to explain their thinking rather than quiz-type questions to which they are expected to give 'the right answer' (that is, questions such as 'what do *you* think is …?' rather than 'what is…?'). Answers to such questions posed during activities may be oral or in writing, drawings, concept mapping, etc. Interpreting what is found in terms of progress towards learning goals enables teacher to decide the next steps and provide feedback to students about how to move forward. The involvement of students in this process, by helping them to understand the goals of their work and standards to aim for, enables them to take some responsibility for, and reflect on, their learning.

Summative assessment

The second purpose of assessment that needs to be considered is for recording and reporting learning at certain times. This refers to achievement over a period of time, not the detailed lesson goals that are the subject of formative assessment. Summative assessment is used to report on students' learning to inform their parents, other teachers and students themselves of their achievements in relation to goals and standards. It is used by schools to keep records and monitor the progress of individuals and groups. When well done, summative assessment also provides exemplars and operational definitions of what it means to understand ideas, and how understanding is revealed through applying learning in various ways. The criteria applied in judging achievement make standards and expectations clear to students, teachers and others. Summative assessment should also help learning, although in the long term rather than in the immediate way of formative assessment.

Summative assessment has a firm grip on curriculum content and pedagogy, and when it is not done well its role can be restrictive. Negative impacts arise when assessment tools do not adequately reflect intended goals – for example, testing knowledge of facts when ability to apply ideas is the aim. The impact is exacerbated by inappropriate use of student outcomes, usually in the form of test scores, for high stakes evaluation of teachers and schools. This use puts pressure on teachers to 'teach to the test' and frustrates attempts to focus curriculum content on big ideas when these are not included in the tests. In the interests of fairness, test-based accountability requires measures that are as reliable as possible. But demand for high reliability has the effect of narrowing what is assessed and compromises validity. There is also research evidence that when testing performance becomes the dominant factor in the classroom, summative assessment drives out formative assessment.

Extending summative assessment methods

Steps that need to be taken to enable summative assessment to play a useful role in developing big ideas include devising and adopting assessment methods that provide valid evidence of understanding. Some efforts are already being made to create methods of assessment that are better aligned with goals of inquiry-based science education. But there is much further to go to ensure that student summative assessment is consistent with the learning processes and pedagogy that promote big ideas. The PISA items for science have extended what is possible in written tests but at the same time have highlighted the limitations of paper-based assessment for individual student assessment. Other methods, not based on question papers are being used, either alone or in combination with written answers, in several countries for high stakes qualifications such as for entry to tertiary education. Examples are: using coursework marks or portfolios of coursework, using practical assignments, project work, presentations and interview. The increasing use of screen-based questions and assignments (as now being developed for PISA) has considerable potential for assessing application of ideas.

Several of these approaches depend on greater involvement and judgements of teachers than is found in traditional external examinations. If these approaches to summative assessment are to provide data of acceptable reliability, steps need to be taken to reduce the bias and errors associated with teachers' judgements. There are several effective ways in which the reliability of teachers' judgments can be improved to the level needed for dependable summative assessment, the main ones being: group moderation; using examples of assessed work; and using a reference test as a check. Group moderation, in which teachers meet to review samples of students' work, has considerable value, not just in improving the reliability of the results but as a form of professional development. The experience enables teachers to deepen their understanding of criteria used in assessment and of the assessment process, with the added benefit of improving teachers' formative assessment. Conducting assessment in this way means that evidence from on-going formative assessment can contribute to summative assessment, bringing these purposes of assessment into harmony rather than conflict.

There is undoubtedly a need for summative assessment strategies and tools that match the content and pedagogy needed for the development of big ideas. But more than this, in many countries, better assessment practice requires a change in policy in relation to how the quality of teaching and school provision for learning schools is evaluated. The use of student test results as the sole measure of teaching quality and school effectiveness, with no regard for differences in student intake, should be replaced by more valid methods, reflecting modern goals of education and related evaluation tools. Without this policy change, even the most valid assessment procedures are undermined by the pressure to meet the requirements, leading to narrow interpretation of criteria and practices unduly influenced by what can be tested.

Summary of implications

To sum up we return to the question of how working towards big ideas will affect students' learning experiences, considering curriculum content, pedagogy and assessment in turn. Even if inquiry-based science teaching and formative assessment are already being practised, there is something further to be added if students are to benefit from gradually developing understanding of the big ideas we have identified. Bringing together points from the above discussion, here are some key features of experience of working with big ideas in mind.

Content

- Teachers are able to explain how lesson goals and activities relate to overall big ideas and so justify the time being spent on these activities.
- Teachers are aware of the successive steps of abstraction in developing bigger ideas.
- Students are working on topics selected because they have, to the teachers and any observer, a clear relationship to one or more big ideas.
- Discussion of their own and each other's investigations and those of scientists, past and present, enables students to understanding how evidence is used to develop ideas.
- Through their activities students are able to develop understanding at an appropriate point in the progression towards big ideas.

Pedagogy

- Teachers help students develop the capabilities and attitudes required to gather relevant evidence to test ideas and answer questions through inquiry.
- Students have opportunities to observe, and where possible explore, events and phenomena at first hand.
- Students have opportunities to raise questions and find answers through inquiry and to reflect on how doing so leads to bigger and more useful ideas.
- Teachers help students to realise how ideas emerging from their classroom inquiries relate to things in their daily lives, to recognise links between new and previous experiences, and between new and previous ideas.

- Students have time to reflect on their investigations and how their ideas may have changed as a result of gathering and using evidence.
- Teachers help students to recognise that claims about causes of phenomena need to be supported by credible evidence and that scientific knowledge is not a matter of opinion, although it may change or be refined in the light of new evidence.

Assessment

- Teachers use formative assessment to promote the active engagement of students in their learning by ensuring that students understand the aims of their work and how to judge its quality.
- Teachers use observations of on-going learning to help students' further learning through giving feedback on how to improve their work and take their next steps in progression towards bigger ideas.
- Teachers use evidence about students' progress to adjust the level of demand and the pace of the work to ensure learning with understanding and progression in ideas.
- Summative assessment methods enable students to show their understanding of ideas by using them to explain events and phenomena in the world around.

6 Implementing big ideas

There are very many aspects of policy and practice that influence the implementation of any change in education. Here we are concerned with three that particularly affect the implementation of working with big ideas in mind:

- the form and content of the written national or state curriculum, which have implications for decisions about content, pedagogy and assessment
- the key role of teachers' content and pedagogical knowledge, which is pivotal in determining the learning opportunities of students
- the formative evaluation of teaching and students' classroom experiences, which informs decisions of how to improve practice and make the best use of professional development resources.

Big ideas in national curriculum documents

It is the role of national curriculum documents to set out the goals of learning and the principles that should guide their implementation but not to propose learning activities, which is the role of teaching units or modules. 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. Although curriculum frameworks specify other learning outcomes, such as science inquiry skills, our main concern here is with how ideas of science are expressed. This should be in terms that everyone can understand – not just teachers, educational researchers and scientists but also parents and others concerned with students' education. Descriptions of progression towards big ideas, such as in Section 4, perhaps with more detail and exemplification, 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 make clear that the process of developing understanding is ongoing and continuous. The aim should be for teachers, parents and others to be able to identify the course of progression towards big ideas, thus making it possible to see how specific activities contribute to this progression.

Expressing big ideas of science

There are now examples of national curriculum documents that include overarching statements of aims expressed in the form of big ideas which, although not precisely the same as the 10 ideas of science we have identified, are sufficiently similar to serve the same purpose. For instance, the guidelines being developed for the K-9 curriculum in France include knowledge that:

> *The Universe is structured from its biggest scale (galaxies, stars, planets) down to the smallest (particles, atoms and molecules).*

But it is how such overall aims are broken down into goals for certain stages or years that is important in communicating the need for continuity and gradual progression in developing big ideas. Big ideas should run longitudinally through the description of learning goals across all stages. To convey the notion of progression in understanding it is not enough to state what is to be learned in terms of topics or concept words such as 'force', 'electricity' or 'materials'. To be useful the statements should indicate the level of understanding or relationships and connections intended at particular stages.

Most curriculum documents, as well as setting out the concepts to be learnt, list science inquiry skills, or practices, to be developed at different stages. Usually these two types of outcomes are listed separately but some recently developed curriculum frameworks express goals at the end of stages, or years, as a combination of skills and concepts. For example, the Scottish curriculum states goals of learning in the form of 'I can …' statements, as in this extract from the outcome relating to the big ideas of biodiversity and interdependence for the end of year four:

> *I can help to design experiments to find out what plants need in order to grow and develop. I can observe and record my finding and from what I have learned I can grow healthy plants in the school.*

The framework for K-12 Science Education in the USA states outcomes in terms of 'what students who demonstrate understanding can do' as a series of statements which combine practices and overall concepts, for example:

> *Investigate the forces between two or more magnets to identify patterns.*
>
> *Use models to explain the effects of balanced and unbalanced forces on a system.*

The form of these statements signals that understanding ideas is to be developed through inquiry and investigation and, at the same time, that inquiry capabilities are developed and used in relation to scientific content. However, although they are clearly not intended to restrict the combination of capabilities and content, there is some arbitrariness in the specified statements in relation to which capabilities and content are linked. Further, the complexity of the statements can obscure the relationship of the ideas at each stage to the overall big ideas.

Level of detail

National curriculum documents vary in the intervals for which learning experiences and outcomes are specified. In some cases what is to be learned is set out year by year and in others only in terms of experiences during, and achievement at the end of, longer periods of two or three years. A detailed curriculum document turns science activities into a routine, aimed at 'getting through the syllabus' to meet requirements rather than spending time to ensure deep understanding. Too much detail limits the potential for teachers to take account of students' interests. Moreover, the more detailed the specification the more problematic the decisions about the exact sequence, and the greater the risk of the detail obscuring sight of the overall aims – the development of big ideas and science inquiry capabilities. The statements of the specific ideas and capabilities that students are expected to develop at particular times ought to be justified in terms of progression towards these overall aims. This is particularly important at boundaries between phases of education such as primary to secondary. When this structure is not made explicit, the content of a curriculum can appear to be no more than an arbitrary selection of what is to be taught, based on tradition or what is easily assessed.

Including ideas about science

The attention given to the big ideas about science in curriculum documents also varies. Where ideas 11 and 12, about the nature of science, are considered at all it is generally to state the assumption that these ideas are developed through engaging in scientific investigation and inquiry. That is, that opportunities to develop science capabilities are also opportunities for reflection on how scientific understanding is built through such activities. However, without more explicit reference in curriculum frameworks, such as in the aims relating to 'working scientifically' in the national curriculum in England, it is easy to see how these opportunities can be missed in planning programmes of study.

In the case of big ideas 13 and 14, about the relationship between science and other STEM subjects and the applications of science, there are various ways in which these are included. In some cases it is through supplying cross-references, usually between the science and mathematics documents. However, these links tend to be regarded as optional when it comes to planning classroom programmes, which is often carried out by individual teachers or single subject groups, rather than in multi-disciplinary teams in which members bring their specialist expertise and together create coordinated learning experiences. Another approach is to embed reference to applications of science in the description of overall aims, as, for example, the discussion of moral and ethical questions arising from technological developments relating to DNA. A third, and possibly more effective way, is to make the links among subject domains an integral part of the curriculum framework. An example is the *Framework for K-12 Science Education*, where engineering and applications of science are identified as a disciplinary core idea in the same way as physical and life sciences. However, the extent to which these various attempts signal the growing importance of understanding links between science and other subject domains, particularly technology, engineering and mathematics, has yet to be seen.

Teachers' understanding of big ideas

The implications for curriculum content, pedagogy and assessment discussed in Section 5 highlight the demands on teachers of the aim of ensuring that students' learning in science gradually builds into a coherent whole, and is not left as a set of disconnected facts. There are consequences for primary and for secondary teachers, for teacher educators and for researchers.

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. These investigations and observations lead to 'small' ideas whose connection to big ideas of science may seem tenuous. Thus, it is more difficult at the primary level to keep in mind the links to the big ideas. Second, in many cases teachers' own education in science has left them without a personal grasp of the big ideas at some level and little opportunity to understand how the pieces of information they do have can be linked together. They are, therefore, likely to be poorly prepared 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 students develop the big ideas. A further difficulty is lack of confidence in teaching science as a result of little personal exposure to scientific activity and the understanding arising from that experience.

On the other hand, primary teachers have some advantages. As generalists, they have the benefit of having closer relationships with their students than do specialist secondary teachers. Also, knowing that they are not experts, primary teachers typically prepare very carefully hands-on science activities for students and provide engaging experiences that students enjoy, enabling them to have a positive response to science. The drawback is that the focus on 'doing' can be at the expense of the discussion and thinking that are needed if the activities are to lead to understanding.

In the secondary school the links between learning activities and big ideas are likely to be rather more obvious than at the primary level. But secondary teachers face the challenge of inquiry in the context of an overcrowded curriculum and may 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 scientific activity that would give confidence in teaching ideas about science. Teaching across all science domains is challenging for anyone; even trained scientists and teachers should have opportunities for continued learning to meet these challenges, which will always be present.

Professional development approaches

For all teachers, the ideal would be personal understanding of big ideas of and about science. The lack of this as a result of their own school science education presents a considerable challenge for initial teacher education or continuing professional development. Of course, the whole of science education cannot be condensed into the limited time available in initial 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.

The 'engagement' here is far more than reading and discussing the narrative descriptions of big ideas, such as those in Section 4. It should take account of current views that learning takes place in the interactions between learners, for adults as well as school students. Discussion with others of the ideas set out in the narratives enables teachers draw on their experiences and those of others in making sense of the evolving 'story'. An individual's understanding is influenced by the views of others as part of a constant interaction between each one and the group. Socially co-constructing their ideas in this way is unlikely to lead to a full grasp of big ideas but will hopefully begin an ongoing process of deepening understanding, one which enables teachers to help students in their progress.

Such experiences should be matched by engagement of teachers in learning some science through inquiry at their own level in order to develop understanding of the nature of scientific inquiry through participation in it. Thus, teachers and trainees need time and opportunities 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 scientific knowledge is created. This provides some preparations for teachers to help students to understand ideas *about* science (ideas 11 and 12 particularly), as well as ideas *of* science.

Just as important as such first-hand experiences in teachers' courses is the provision of continuing support for developing understanding of science and of effective pedagogy in a form that can be accessed throughout their active lives. The internet can have a key role as a source of information, preferably in the form of tailor-made electronic publications designed to meet the needs of teachers. In addition, personal understanding of science and how to teach particular concepts can be provided, for instance, through direct contact with more experienced teachers and scientists. There is evidence that teachers learn very effectively from other teachers and that access to others' practice is an important part of the many interacting aspects involved in the implementation of changes such as are required for working towards big ideas through inquiry-based teaching.

The analysis of teachers' professional development needs, and knowing how to cater for them in particular cases, are areas where more research is needed. However, in the next section we offer some preliminary ideas about how to identify the aspects their practice where teachers may need help in relation to teaching for big ideas.

Formative evaluation of teaching for big ideas

We use the word evaluation here because the focus is teaching, not the assessment of students' learning. The purpose is to collect and use data to improve teaching of those aspects of classroom practice that enable students to develop their understanding of big ideas. We are not concerned here with the whole gamut of features of effective practice in science education, only with this key part of it, although it will include many of the elements of inquiry-based learning since this is so much a part of developing understanding in depth.

Indicators of students working towards big ideas

Formative evaluation in this context means collecting and using data about relevant aspects of teaching to identify where practice meets expectations and where improvements may be required. In this respect it has a similar purpose in relation to teaching as formative assessment has in relation to students' learning. Whilst learning is assessed in relation to the goals of activities, in the case of evaluating teaching it is in relation to indicators, or standards, of effective classroom practice. The first step in evaluation, therefore, is to establish such indicators. These may be expressed in terms of students' activities and ways of working that help their understanding of big ideas. For example, indicators of good practice are likely to include students having such opportunities as to:

- understand the purpose of their activities
- explore new objects of phenomena informally and 'play with ideas' as a preliminary to more structured investigation
- make links between new and previous experience
- work collaboratively with others, communicating their own ideas and considering others' ideas
- present evidence to support their arguments

- engage in discussions in defence of their ideas and their explanations
- apply their learning in real-life contexts
- reflect self-critically about the processes and outcomes of their inquiries.

However, students' opportunities for these experiences depend on teachers' planning and how these plans are carried into action. So using indicators relating to teaching is a more direct approach to identifying where teachers may need help. A set of indicators describing agreed aspects of practice has a dual purpose – pointing to the data to be collected and acting as criteria for judging where teaching is or is not meeting the expected standards.

Indicators of teaching towards big ideas

The following are suggestions to illustrate indicators and the process of evaluation in relation to teaching that aims to develop big ideas. Indicators used in practice should emerge from discussions among teachers about how to describe teaching which has this aim. These discussions serve a formative function, helping teachers to develop their understanding of what is involved as well as ensuring that evaluation is completely open, so that everyone concerned knows the reasons for collecting and the use to be made of the evidence. It is important for teachers to know the basis of the evaluation if they are to take part willingly to review their practice.

It is quite helpful to express the indicators as questions. For example, does the teacher:

- have a clear idea of how the students' activities help them towards understanding one or more of the big ideas?
- allow time for students to explore new situations and discuss their initial ideas in an unstructured way?
- help students to recognise links between new and previous experience and ideas?
- discuss with students how the ideas emerging from their inquiries relate to experiences in their daily lives?
- consciously build bigger ideas by showing how particular ideas can explain a range of events or phenomena?
- discuss with students how their collection and use of data enables them to test ideas in ways similar to scientists?
- help students to reflect on their investigations and build up ideas about the nature of scientific activity?
- ensure that students learn from experience of ideas or constructions that 'don't work' and do not regard this as failure?
- take the opportunity to discuss how scientific ideas are used in scientific investigations or engineering advances that feature in the news?
- as appropriate to students' ages, use examples from history to show how scientific ideas have changed and the reasons for this?

Gathering data for evaluation of teaching

The indicators themselves signal the useful sources of information for the evaluation. These include: teachers' lesson plans; teachers' records of students' progress; students' notebooks; talking with students; and, if possible, observation of teaching. It is useful to have someone

– a mentor, teacher educator or another teacher – to observe teaching. Teachers might collaborate in collecting information relating to the indicators by observing each other's lessons. But if the help of an observer is not possible, teachers can still obtain useful information by reviewing their own plans, notes and records (including videotapes of their lessons) and making time for talking to students to find out what they think about their work. Indeed, for teachers not used to having another person in the classroom self-evaluation may be preferred, at least initially.

Students' notebooks, available to teachers and observers, constitute valuable sources of information about students' activities, providing a record of what, and how, science has been taught. The analysis of students' notebooks can provide evidence of a student's communication, their conceptual and procedural understanding and the quality of a teacher's feedback to the student.

Interpreting evaluation data

Of course, teachers will not provide in every lesson or sequence of activities experiences of all the kinds indicated in a list such as the one above. However, if there is no evidence of certain items over a period of time, it is important to ask 'why not?' if the evaluation is to fulfil a formative purpose. The reasons may point to the help that is needed in some area of understanding of content or pedagogy. Evaluation of this kind is particularly relevant as part of professional development when some quite fundamental changes in teaching are being introduced, such as inquiry-based teaching and working with big ideas. It need not always address the whole range of indicators but can be used to provide feedback on particular aspects of practice that a teacher is trying to change. It is essential that the teacher remains in control of the process which should be seen as part of professional learning, not a matter of making judgements on how well the teacher is doing.

Concluding comment

Implementing any change in education or other areas of activity depends on several factors: recognising the need for change; belief that the proposed change will bring about the desired effect; and accepting the consequences for the many interconnected factors that determine practice in education.

The reasons for change in science education have been evident in the reports of students' negative perceptions of its value and interest to them. Foremost among the factors responsible for this are over-crowded and over-detailed curricula, assessment that is dominated by tests that encourage teaching of disconnected facts, and clinging to teaching methods that inhibit change to inquiry-based pedagogy. The result is that science education in many parts of the world has been failing to prepare young people for a world rapidly being transformed by applications of science in technology and engineering. Such preparation requires that everyone, not just those likely to take up science-based occupations, needs a general understanding of key ideas of science and about science that enable them to take part as informed citizens in decisions that affect their own and others' well-being.

In this document we have reiterated and expanded on the case for framing the goals of science education in terms of a set of over-arching ideas – called big ideas because they explain a range of related phenomena. We have noted the arguments and offered some evidence of the potential benefits to be gained by identifying a small number of powerful ideas, not the least of these being to free up space for inquiry-based pedagogy to be implemented. Enabling students to experience and value the collection and use of evidence in scientific activity is central to developing understanding of the world around and how we make sense of it. We argue that a curriculum framed in terms of big ideas is necessary to adopting an inquiry-based approach.

To bring about change in how the goals of science education are conceived and expressed requires more than a revision of curriculum documents. What happens in classroom is influenced by many interconnected practices, the main ones, discussed here, being student assessment, teacher education and pedagogy. However there are many other influential factors, such as how schools are organised, how teaching and teachers are appraised and evaluated, the role and expectations of parents, the support given by local administrator and inspectors and, of course, government policy. Real change requires coordination of all these sources of influence. Teachers are ultimately responsible for students' learners' experiences but they cannot make real change alone; in many cases a change in policy is required so that innovation is not stifled by existing practices.

Profiles of seminar participants

Derek Bell

Professor Derek Bell is a teacher, researcher, advisor and advocate for improving and enriching education for all. He worked in schools and universities before becoming Chief Executive of the Association for Science Education (ASE) and Head of Education at the Wellcome Trust. He remains very active in education, nationally and internationally, through his consultancy (Campanula Consulting), committee and advisory work and has a wide range of publications. He is currently a trustee of the IBM Trust UK, Understanding Animal Research and Centre of the Cell in the UK, a member of the Inter Academies Panel Global Science Education Committee and of the judging panel for the European Union Competition for Young Scientists. He was awarded an honorary Doctorate of Education by Manchester Metropolitan University in 2011. Derek is Director of LEARNUS, Professor of Education in the College of Teachers and a visiting research associate at UCL Institute of Education, London.

Rosa Devés

Professor Rosa Devés received a PhD in biochemistry from the University of Western Ontario, after which she joined the Department of Physiology and Biophysics at the Faculty of Medicine, Universidad de Chile. She taught at the undergraduate and graduate level in cell physiology and participated in the development of graduate education including the founding of the PhD Programme in Biomedical Sciences which she directed for two periods of five years. She also contributed to the establishment of the Institute for Biomedical Sciences that resulted from the merge of twelve departments of basic and preclinical sciences. She was vice-director of the Institute from 1997 to 2000.

In parallel with her scientific and academic career she has been engaged in the improvement of school science education, collaborating between 1999 and 2002 with the Curriculum and Evaluation Unit at the Ministry of Education as coordinator of the science teams that were developing the new curriculum. In collaboration with the US and French Science Academies she initiated, in 2003, with Professor Jorge Allende the ECBI Programme (Inquiry based Science Education Programme) which works in partnership with the Ministry of Education, the Academy of Sciences and universities with the aim of bringing high quality science education to all children.

As provost of the University of Chile from 2010 to 2014 she led two projects which led to the development of Education as a strategic area for the University and the strengthening of equity and inclusion with the aim of generating more opportunities for students coming from underprivileged backgrounds. In July 2014 she was appointed Vice-President of Academic Affairs at Universidad de Chile. Since 2003 she has been a corresponding member of the Chilean Academy of Sciences.

Hubert Dyasi

Professor Hubert M. Dyasi, PhD, is a specialist science teacher educator. He has designed, directed, and implemented inquiry-based science education programmes worldwide and made peer-reviewed professional presentations at numerous conferences and meetings. He has also contributed chapters to, and co-authored books such as *America's Lab Report* (National Academy Press, 2005); *Designing Professional Development for Teachers of Science and Mathematics* (Corwin Press, 2003); *Inquiry and the National Science Education Standards: A Guide for Teaching and Learning* (National Academy Press, 2000); and *The National Science Education Standards* (National Academy Press, 1996). Among his awards are: Distinguished Service to Science Education, Outstanding Educator, Membership of the National Research Council's Committee on K-12 Science Education and Visiting Scholar at California Institute of Technology and at All Souls College (Oxford University). He is a Fellow of the National Institute for Science Education and a member of the council of the Inter-Academy Panel's Science Education Programme.

Guillermo Fernández de la Garcia

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, ICT 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 and selections of articles from the Magazine are still distributed by the Mexican Ministry of Education. The meetings of children and scientist that CHISPA organised evolved to become the “Saturdays and Sundays in Science” programme that has been operated by the Mexican Academy of Sciences.

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. He organized jointly with the Ministry of Education and the Mexican Academy of Science the initial trial of activities in Mexico of the Science and Technology for Children curriculum. 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 where she set up the Centre for Research and Development in Primary Science. In 1990 she moved to Edinburgh to become Director of the Scottish Council for Research in Education until 1999. She now works as a consultant from her home in Scotland. She led several projects in research, professional development and curriculum development and published several books on science education and assessment.

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 the first chair of the OECD PISA Science Expert Group 1998-2003. She chaired a working group of the Royal Society (State of the Nation Report on Science and Mathematics Education 5-14). 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 the ASE in 2001. In 2008 she was awarded, jointly with Guillermo Fernández de la Garza, the International Purkwa Prize and received special recognition of contribution in promoting inquiry-based science education by the Mexican Ministry of Education and INNOVEC in 2011.

Pierre Léna

Professor Pierre Léna is Emeritus Professor of astrophysics at the Université Paris Diderot. At the Observatoire de Paris, he has contributed to infrared astronomy, to the European Very Large Telescope (VLT) in Chile, and to new optical techniques applied to astronomical images. He directed the Graduate school of Astronomie and Astrophysique d'Ile-de-France for many years. He is Member of the French Académie des sciences, the Academia Europeae and the Pontifical Academy of Sciences.

His involvement in education developed as Chairman of the Institut national de recherche pédagogique (1991-1997). With Nobel laureate Georges Charpak he spearheaded a reform of science education in French primary schools, the inquiry-based project La main à la pâte, supported by the Académie des sciences. The project developed classroom procedures and resources, and became recognised officially in the French curriculum in 2002. The success led the Académie to establish in 2005 a permanent office, which Pierre led until 2011, to manage these projects, including teacher training. Since 2012, the Académie, along with the Ecoles normales supérieures (Paris and Lyon) created a Fondation de coopération scientifique La main à la pâte, with a staff of 25, dedicated to science education, international cooperation and a limited amount of research. Books and other resources are published and training session organised every year. Pierre became its first president (2011-2014). See www.fondation-lamap.org and www.academie-sciences.fr/enseignement/generalites.htm

Robin Millar

Professor Robin Millar is Emeritus Professor of Science Education at the University of York, England. With a degree in theoretical physics and a PhD in medical physics, he trained as a teacher and taught physics for eight years in secondary schools in Edinburgh before moving to the University of York in 1982.

Robin has published widely on many aspects of science teaching and learning. His main areas of research interest are students' learning in science, science curriculum design and development, and assessment of science learning. He has directed research projects on investigative practical work in science, and young people's images of science. From 1999-2004, he was coordinator of the *Evidence-based Practice in Science Education* (EPSE) Research Network. He has been involved in several major curriculum development projects, including *Science for Public Understanding,* and the *Twenty First Century Science* suite of courses for secondary school students.

Robin was a member of the UK group in the EU *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)* study in 2006 and in 2015. He was President of the European Science Education Research Association (ESERA) from 1999-2003 and President of the UK Association for Science Education in 2012.

Michael Reiss

Michael Reiss is Professor of Science Education at UCL Institute of Education, Visiting Professor at the Universities of Leeds and York and the Royal Veterinary College, Honorary Fellow of the British Science Association and of the College of Teachers, Docent at the University of Helsinki, Director of the Salters-Nuffield Advanced Biology Project and a Fellow of the Academy of Social Sciences. The former Director of Education at the Royal Society, he has written extensively about curricula, pedagogy and assessment in science education and has directed a very large number of research, evaluation and consultancy projects over the past twenty years funded by UK Research Councils, Government Departments, charities and international agencies.
See www.reiss.tc.

Patricia Rowell

Patricia M. Rowell is Professor Emeritus in the Department of Elementary Education at the University of Alberta. Her research interests focus on the nature of discursive strategies employed in the teaching and learning of primary science in both formal and informal settings. Her research has been funded by a series of federal grants. She is a founding member of the Centre for Mathematics, Science and Technology Education at the University of Alberta, and has been responsible for the production of inquiry–based teacher resources distributed province-wide. She has worked as a science educator in Namibia and Botswana (2 years in each country), and conducted workshops in South Africa, China, Chile and Australia. Pat received degrees in Biochemistry (B.Sc. Honours, London; M.Sc., Oxford) and Science Education (B.Ed., Ph.D., University of Alberta).

Wei Yu

Wei, Yu is Professor and founder of Key Laboratory of Child Development and Learning Science of the Ministry of Education, at Southeast University, China. During her long career as a teacher and researcher in electronics, her significant achievements include 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 of Education.

Since 1994 she has been actively involved in school science education reform as a member of ICSU-CCBS (1994-2001) and of the IAP Science Education Programme since 2002. Wei Yu has developed new interdisciplinary research 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. She was the chairperson of the Revision Committee of National Standard of Science Education in Primary Schools in China. In 2010 she and her team received the First Ranking National Price of Education Reform in Chinese Basic Education. She was awarded the PuRkwa prize by the French Academy of Sciences and the Saint Etienne Mining School for innovative practices in science education. She is an Academician of CEA and received Honorary Doctorates from nine universities outside Mainland China.

List of sources

AAAS (American Association for the Advancement of Science) (1993) *Benchmarks for Science Literacy. Project 2016*. Oxford: Oxford University Press.

AAAS (2001) *Atlas of Science Literacy*. Washington, DC: AAAS and NSTA.

Abrahams, I., and Reiss, M. J. (2012) Practical work: its effectiveness in primary and secondary schools in England, *Journal of Research in Science Teaching*, 49(8), 1035-1055.

Alberts, B. (2008) Considering science education. Editorial, *Science,* 319, March 2008.

Alexander, R. (ed.) (2010) Children, their World, their Education. Final report and recommendations of the Cambridge Primary Review. London: Routledge.

Biosciences Federation (2005) *Enthusing the Next Generation*. London: Biosciences Federation.

Bransford, J.D., Brown, A. and Cocking, R.R. (eds) (2000) *How People Learn, Brain, Mind, Experience and School.* Washington, DC: National Academy Press.

Bruner, J.S. (1960) *The Process of Education*. New York: Vintage Books.

Butler, R. (1988) Enhancing and undermining intrinsic motivation: the effects of task-involving and ego-involving evaluation on interest and performance, *British Journal of Educational Psychology,* 58(1), 1-14.

Carnegie and Institute for Advanced Study (2010) The Opportunity Equation Transforming Mathematics and Science Education for Citizenship and the Global Economy. New York: Carnegie IAS.

Concoran, T., Mosher, F.A. and Rogat, A. (2009) *Learning Progressions in Science*. Philadelphia, PA: Centre on Continuous Instructional Improvement, Teachers College, Columbia University.

Devés, R. (2009) Science Education Reform in Chile (1990-2009) Paper prepared for the 2009 Loch Lomond Seminar.

Duncan, R.G , Rogat, A.D. and Yarden, A. (2009) A learning progression for deepening students' understandings of modern genetics across the 5th–10th grades*. Journal of Research in Science Teaching,* 46 (6), 655–674.

Duschl, R. A., Schweingruber, H.A. Shouse, A.W. (2007) *Taking Science to School: Learning and Teaching Science in Grades K-8.* Washington DC: The National Academies Press.

European Commission (2007) *Science Education Now: A renewed Pedagogy for the Future of Europe*. (Rocard Report) Brussels: European Commission.

Fernandez de la Garza, G. (2009) Brief overview of the evolution of the science curriculum for the elementary schools in Mexico. Paper prepared for the 2009 Loch Lomond Seminar.

Gustafson, B.J. and Rowell, P.M. (2000) Big ideas (and some not so big ideas) for making sense of our world. A resource for Elementary Science Teachers. Edmonton: University of Alberta.

Harlen, W. (2013) *Assessment and Inquiry-Based Science Education: issues in policy and practice*. Global Network of Science Academies (IAP) Science Education Programme: Trieste, Italy. www.interacademies.net/activities/projects/12250.aspx

Harlen, W. (2009) Teaching and learning science for a better future, *School Science Review*, 90 (333), 33 -41.

Honey, M., Pearson, G. and Schweingruber, H. (eds) (2014) STEM *Integration in K-12 Education: Status, prospects and an agenda for research.* Washington DC: The National Academies Press.

Howard-Jones, P., Pollard, A., Blakemore, S-J., Rogers, P., Goswami, U., Butterworkth, B., Taylor, E., Williamon, A., Morton, J. and Kaufmann, L. (2007) *Neuroscience and Education: Issues and Opportunities*, London: TLRP/ESRC.

La main à la pâte (1998) Ten principles of teaching. http://www.fondation-lamap.org/fr/page/105/principes-et-enjeux

La main à la pâte (2014) www.fondation-lamap.org

Le Socle commun des connaissances et des compétences (France, 2006). http://cache.media.eduscol.education.fr/file/socle_commun/00/0/socle-commun-decret_162000.pdf

Learning and Teaching Scotland/SQA (nd) *Curriculum for Excellence: Sciences experiences and outcomes.*http://www.educationscotland.gov.uk/Images/sciences_experiences_outcomes_tcm4-539890.pdf

Léna, P. (2009) Big ideas, core ideas in science - some thoughts. Paper prepared for the 2009 Loch Lomond Seminar.

Mansell, W. James, M. and ARG (Assessment Reform Group) (2009) *Assessment in Schools. Fit for Purpose? A commentary by the ESRC Teaching and Learning Research Programme*. London: ARG and TLRP.

Massachusetts Science and Technology/Engineering Curriculum Framework (October 2006). http://www.doe.mass.edu/frameworks/scitech/1006.pdf

Miaoulis, I. (2010) K-12 Engineering – the Missing Core Discipline. In (eds) D. Grasso and M. Brown Burkins *Holistic Engineering Education beyond Technology*. New York: Springer.

Millar, R. (2009) 'Big ideas' in science and science education. Paper prepared for the Loch Lomond seminar.

Millar, R. and Osborne, J. (1998*) Beyond 2000. Science Education for the Future*. London: King's College School of Education.

Mohan, L., Chen, J. and Anderson, C.W. (2009) Developing a multi-year learning progression for carbon cycling in socio-ecological systems. *Journal of Research in Science Teaching,* 46 (6), 675–698.

NAEP (2008) *Science Framework for the 2009 National Assessment of Educational Progress.* National Assessment Governing Board, US Department of Education.

NRC (National Research Council) (1995) *National Science Education Standards*. Washington DC: The National Academies Press.

NRC (National Research Council (2012) *A Framework for K-12 Science Education.* Washington DC: The National Academies Press.

NRC (National Research Council (2014) *Developing Assessment for the Next Generation Science Standards*. Washington DC The National Academies Press.

Oates, T. (2009) Missing the point: identifying a well-grounded common core. Comment on trend in the development of the National Curriculum. *Research Matters*, October 2009.

Oates, T. (2012) *Could do better: Using international comparisons to improve the national Curriculum in England*. Cambridge Assessment www.nationalnumeracy.org.uk/resources/30/index.html

OECD (2007) Understanding the Brain: The Birth of a Learning Science. Paris: OECD.

Pellegrino, J.W., Chudowsky, N. and Glaser, R. (eds) (2001) *Knowing what Students Know: The Science and Design and Educational Assessment.* Washington, DC: National Academy Press.

Songer, N.B., Kelcey,B. and Gotwals, A.W. (2009) How and when does complex reasoning occur? Empirically driven development of a learning progression focused on complex reasoning about biodiversity. *Journal of Research in Science Teaching,* 46 (6), 610–631.

Twenty-First Century Science specifications; Science Explanations and Ideas about Science http://www.ocr.org.uk/campaigns/science/?WT.mc_id=sciencecp_300310

Wilson, M. and Draney, K.(2009) On coherence and core ideas. Paper commissioned for the NRC Board of Education meeting, August 17 2009.

Wei Yu (2009) *A Pilot program of "Learning by Doing" in China's Science Education Reform*. Nanjing: Research Centre of learning Science, Southeast University.

Wellcome Trust (2014) *How neuroscience is affecting education: a report of teacher and parent surveys.* www.wellcome.ac.uk/stellent/groups/corporatesite/@msh_peda/documents/web_document/WTP055240.pdf

Zimba, J. (2009) *Five areas of core science knowledge: What do we mean by 'STEM-capable'?* Paper prepared for the Carnegie – Institute for Advanced Study Commission on Mathematics and Science Education (see Carnegie and IAS).

Five years ago, in 2010, the publication of *Principles and Big Ideas of Science Education* set out arguments that students' science education should enable them to develop a relatively small number of big ideas of science and about science. Since then the case for action has been strengthened by events in education and in daily life. The response from users in many countries has confirmed that the ideas identified remain relevant and are being reflected in reform in some national curricula.

However the potential benefits of greater depth in learning, rather than uncoordinated breadth, depend on changes in classroom practice. Therefore this follow-up publication, reporting further work by the same international group of scientists and science educators, gives further attention to what is involved in working towards big ideas. Following a review of the big ideas, implications for curriculum content, pedagogy, formative and summative assessment, professional development and the evaluation of teaching are discussed.

iap
the global network of science academies