Third edition

Science 5–11

A guide for teachers

A David Fulton Book

Alan Howe, Christopher Collier, Kendra McMahon,
Sarah Earle and Dan Davies

Science 5–11

This third edition of the bestselling textbook *Science 5–11* has been fully updated to provide a synthesis of research and best practice in teaching and learning that focuses on successful ways to engage and motivate young scientists.

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Alan Howe is Head of Department for Education Studies, Bath Spa University.

Christopher Collier is Senior Lecturer in Education, Bath Spa University.

Kendra McMahon is Senior Lecturer in Education, Bath Spa University.

Sarah Earle is Senior Lecturer in Primary Education, Bath Spa University.

Dan Davies is Dean of Cardiff School of Education, Cardiff Metropolitan University.

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and Dan Davies

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This book is dedicated to all the past members of the Bath Spa University primary education science team.

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Introduction

Welcome to this fully updated third edition of *Science 5–11: A guide for teachers*. The five authors have pooled their knowledge and experience in science education (collectively, more than 100 years-worth!) to bring you the latest thinking, research and practice in primary science.

In spite of the many pressures and demands on the profession, teaching continues to be one of the most rewarding of careers. People become teachers for many reasons, but often it is because they believe they can inspire children to find learning fascinating. There are so many things to learn and so many ways to know; we think science offers teachers and learners a great deal in both respects. By being scientific we can satisfy our curiosity, ask new questions and make informed decisions in our lives. Science can focus our attention, stimulate our thinking and help us appreciate the wonders of the natural world. Through teaching science we can help children see new sights, think new thoughts and understand a little better why the world (and beyond) can be an enthralling place.

This book is organised somewhat differently from others on primary science currently available. In recent years there has been a renewed emphasis on teachers' own subject content knowledge, and many books aim to help teachers ensure their understanding is secure. Other books look at pedagogical knowledge (Shulman 1987) in detail and offer good advice regarding the many facets of teaching science: planning, assessment, progression and so on. However, for primary teachers in England and many other countries, daily classroom experience is of a science curriculum broken down into traditional disciplines (corresponding approximately to biology, chemistry and physics, respectively) and further sub-divided into 'topics' – plants, forces, etc. Although this is a culturally imposed structure, as a team of teacher educators we have realised that each science topic offers teachers particular opportunities and particular challenges. In a sense, they all have their own pedagogies. For example, the teaching of 'forces' needs to be approached quite differently to 'humans and other animals', which requires a different pedagogy to teaching 'Earth and beyond'. Because these divisions sometimes do not equate to how children understand the world, we need to identify places where strong and productive links can be built between children's experiences and the science curriculum. We have, therefore, within each chapter, sought to provide the reader with a synthesis of content and pedagogy that is focused on answering the question 'How should I best teach this area of science?'

We also know that primary teachers constantly reflect on their teaching and wonder if they are 'good' at their job. We suggest the following criteria are useful to answer that question and they inform subsequent chapters.

Good science teachers:

- have clear personal aims for science teaching;
- have an understanding of the nature of science;
- have an understanding of the 'processes of science' and how science creates knowledge – that ideas are tentative, and are based on interpretation of evidence;
- have sufficient understanding of the 'big ideas' of science to see where learning is leading and to avoid giving misleading information;
- value children's existing ideas;
- have a knowledge of some common alternative ideas that children hold;
- have a repertoire of teaching strategies they can use responsively and creatively;
- feel excited about teaching science.

We intend that this book will be a valuable starting point for anyone who wishes to teach science in a creative and inspiring way. Students in initial teacher training and primary teachers who are relatively new to the profession will find here a framework for teaching science that is both relevant and engaging for primary children. This framework is grounded in personal experience, theory and research, in line with our commitment to evidence-based practice. It will be introduced in the first chapter and developed in subsequent chapters as we consider what it means for teaching various topics within the primary science curriculum. We hope that the book will also be useful for those who are more experienced practitioners. Rather than present a prescriptive model for teaching science, we explain approaches and strategies that teachers can adopt, develop and use creatively with the children in their own classes. Teachers who have the additional responsibility of being science subject leaders or co-ordinators may also find it useful in helping them with supporting colleagues, and in reflecting on progression across the whole primary school. We focus on their role in Chapter 5.2.

Organisation of the book

In this third edition we have divided the book into five sections. In Section 1 we consider the aims of primary science, introduce our view of the nature of science and explore the central role of scientific enquiry. For this third edition we have ensured the level of discussion and debate within the section are a good starting point for students who are studying at 'Masters' level, and we offer suggested further reading and give reference to research. There is a full discussion of the importance of talk, specifically dialogue, between teachers and learners.

Sections 2, 3 and 4 take in turn the teaching of Biology, Chemistry and Physics. Within each section you will find chapters on a range of science topics, such as 'living things', 'materials and their properties' and 'electricity'. Here we explore in depth the issues for teaching and learning in that topic. For ease of reference, each topic-based chapter will follow a similar pattern:

Purpose of this chapter

A series of bullet points will set out the aims of the chapter for the reader.

Introduction

In the introduction to each chapter we will explain the relevance of the topic for primary children, and in terms of developing the 'big ideas' of science.

Progression (from the early years to the beginning of secondary school)

What are the key concepts that are to be developed within this conceptual area? What kinds of expectations might we have of children at various stages in their primary education and where is this leading? A table will summarise the subject knowledge related to those 'key ideas' for teachers to access at a glance, we give you some 'teachers' self-assessment questions' to test your own subject knowledge and we recommend sources that would support you in further developing your subject knowledge of these concepts.

Cross-curricular opportunities

Teachers are always keen to make learning as relevant and engaging as possible for their class. One way to achieve this is to teach in a way that creates links between different curriculum subjects. In this section we outline for each science topic the range of opportunities for cross-curricular planning. The context within which scientific ideas are presented is vitally important in motivating children and ensuring that the ideas connect with their own lives sufficiently to make sense. We also provide suggestions for how to introduce children to the topic in question in ways that will excite their interest and be meaningful and relevant for them.

Assessment for learning

In this section we select and exemplify those strategies for eliciting children's exciting ideas that are most appropriate for the topic. We also explore common alternative ideas that children may hold, preparing teachers for what they might encounter in their own classrooms. This will draw on a range of established research and literature. *Key questions* for formative assessment will be identified (these are *italicised* for ease of reference). The relationship between elicitation and formative and summative assessment will be considered in the context of the particular conceptual area.

Working scientifically

Here we focus on the particular aspects of scientific enquiry that could be developed through this topic, drawing on the categories identified in Section 1. The intention is both to support the reader in understanding the different forms enquiry can take and to suggest possibilities for enquiries as interventions. This section also addresses issues of assessment of scientific enquiry relevant to the conceptual area.

Classroom management

Primary teachers often find the organisational aspects of science, particularly practical work, a challenge. In this section we offer advice and raise awareness of health and safety issues relating to the conceptual theme.

Summary

A brief resume of the chapter contents.

Discussion questions

These are intended to further develop your thinking and understanding of the chapter content. Some aim to promote critical thinking at 'Masters' level.

Section 5 is designed to support teachers in thinking beyond the classroom to issues that impact on the whole school. This is addressed to all teachers but is of particular relevance to subject leaders, headteachers and those with a role in developing a schools strategic direction. Three key aspects are discussed: assessment, subject leadership and transisitions.

In writing this book we have drawn on our wide range of experiences and expertise gathered from a variety of perspectives: as primary teachers, advisory teachers, university tutors and teacher trainers. We must also acknowledge that this book would not have been possible if we had not been fortunate enough to work within a science education community that is creative, dedicated and generous. We have drawn ideas together from past colleagues, students, trainees and teachers as well as from published sources. We hope we have acknowledged everyone and offended no one in the process.

SECTION

1

Teaching science – how theories inform practice

Purpose of this section

In this section we lay out some of the key principles, values and theories that underpin the other sections of the book.

After reading this chapter you should have:

- reflected on the aims and purposes of teaching science in the primary school;
- an understanding of the nature of science;
- an understanding of some theories of learning in relation to science;
- considered the implications of theory on the pedagogy of science.

What are the aims of primary science?

We believe that every person must have a good science education so that they can participate in society as a scientifically literate individual and make informed choices about their world and their future. We know that lifelong attitudes and enthusiasms can be initiated by powerful experiences during childhood and we believe primary educators have an important responsibility to ensure that children's experiences of science are positive. It is not the main aim of primary science to produce biochemists, engineers, doctors, ecologists, astronomers and wildlife photographers yet these may be the future professions of the young children sat on the carpet or at their desks in front of you. There may be other children who already have begun to develop a sense that science is 'difficult', 'boring' or 'not for me'. Individuals will have a greater or lesser need for an understanding of particular aspects of science in their everyday lives, depending on their roles and interests, and primary science provides the broad foundation for lifelong learning but primary science also has an even broader agenda. We also believe no group, for example women, should be excluded by the ways in which science is presented in school. Teachers have a responsibility to enable all children to access a full science education. Stereotypes about science and scientists must be actively challenged.

Looking beyond the need of the individual, we argue that an important aim of science education as a whole is establishing 'scientific literacy' across the population. Science is not something scientists do in isolation from the rest of society. It requires funding, and so the providers of these funds must consider the research to be worthwhile. In many cases science is supported by public money, via taxation. Science is also subject to government regulation, such as ethical guidance for the use of animal experiments and standards for testing medicines. So it is not just scientists that need to make decisions about science and the directions in which science goes. In our roles as consumers, parents, citizens and voters, everyone has a stake in science and, arguably, a responsibility for it. In a scientifically literate society people would engage with science issues that affect our lives and take an active part through democratic processes and personal decisions. In our experience, primary-aged children begin to develop viewpoints on issues that have an ethical as well as a scientific basis, such as how farm animals should be treated and how habitats should be protected. It is likely they will need to think about many such complex issues and participate in debate as they grow up.

Last but not least, we believe that the most important aim of primary science is to foster children's deep appreciation of the world around – what is sometimes refered to as 'awe and wonder'. We do this by encouraging a keen eye for observation and a keen mind for questioning. We might see that having to 'introduce' the scientific world to children is a great responsibility. In fact it is also a great pleasure, as children introduce us to the world as they see it, we learn too. Through science children will develop an understanding of how natural phenomena, living things and the environment are closely related. This is worthwhile because the world is fascinating, it can amaze, and such encounters enrich our lives.

Here we have outlined some of the beliefs and values that give the authors a passion for science and science teaching. What will your reasons be for teaching science?

What is science?

Arguably, some of our above aims could be achieved through art, through literature, or perhaps through more everyday experiences such as going out for a woodland walk. So what is it that makes the scientific study of the world a distinct and valuable approach? Science provides a unique way of making sense of the world by offering a way of responding to many of those 'why?' questions that children have and providing some plausible (but often tentative) answers. Science emphasises knowledge gained through observation and investigation (i.e. it is *empirical*) but also values evidence, reasoning and critique. Osborne (2015) argues that science is fundamentally about developing *ideas*. It provides people with a means of engaging with the world in their everyday life, which is empowering rather than fatalistic or superstitious. There are other ways of understanding the world too – the arts, humanities and sciences are not in opposition or on different 'sides', rather they can be complementary ways of looking at the world.

Scientific knowledge is tentative; the explanations are the best we have at the moment, but there is always the possibility that these theories will be challenged or replaced in the light of new ideas and evidence. If children are to really understand science, this fundamental view of the nature of science must run through all of science teaching. Science is not standing still – ideas are changing, new evidence is being produced, and creative thinking generates new questions and explanations. Critical thinking tests explanations. Is using a mobile phone dangerous to our health? What are the possible impacts of light pollution? At any one time, scientists may disagree about explanations, and different studies may provide conflicting evidence yet the argument that science should be studied as one of the great cultural achievements of modern times is a compelling one.

Scientific knowledge could be defined as the ideas any individual constructs as a result of scientific reasoning. Ask yourself 'What happens to your food after you have swallowed it?', 'Where does the Sun go at night?', 'Why are house bricks heavier than balloons?' Now consider where these ideas came from. We all enage in scientific reasoning as we try to make sense of what we see. Osborne (2015, p. 17) identifies types or styles of reasoning that could be summarised for primary education as: experimenting, sorting/classifying, pattern-seeking, hypothesising, and mathematical reasoning. Osborne also identifies a sixth type, that of 'historical-based thinking' (p. 17) which encompasses the 'evolution' of big ideas of science over the centuries. This reasoning has resulted in a body of knowledge that is held by the scientific community as a whole, including inherent tensions, contradictions and uncertainties. This presents particular challenges for teaching science that we hope to address in subsequent chapters. We need to consider how this tentativeness can be communicated, while at the same time acknowledging the value of the existing body of knowledge. We also need to help children to get to grips with ideas that have developed over thousands of years.

The time-scale for changes in the better-established concepts in science seems to be sufficiently long that there is a fairly stable body of knowledge that primary children can get to grips with that is likely to remain useful for years to come. The National Curriculum (NC) for England is one attempt to select aspects that might be relevant and accessible for primary-aged children, and this book is largely based on that selection. Other authors (Millar and Osborne 1998, Harlen *et al.* 2015) have emphasised the importance of the 'big ideas' in science – concepts such as particle theory, energy, evolution and the formation of the Earth – that unify different branches of science, and are powerful 'explanatory stories' in how, as a culture, we currently make sense of the world. We also draw your attention to these big ideas in turn in subsequent chapters and so will sometimes go beyond the prescription of the local NC.

There has been a recent trend towards people being more sceptical about 'experts' and having a lack of trust in their pronouncements. It is reasonable to be sceptical about who is defined as, or appoints themselves as an 'expert'. We should question their sources of funding, their credentials and their vested interests. Indeed, scientific attitudes include questioning what others say. However, when there is a rejection of scientific reasoning it can be due to unrealistic expectations of the kind of answers science can generate. It does not always produce certainties, though findings have sometimes been presented as such in media headlines that announce miracle cures or predict impending doom. If teachers see scientific ideas as indisputable facts, and present them as such, they are misleading children and giving them a false understanding of the nature of science. Weighing evidence, understanding probability and assessing risk are all part of understanding how to make judgements and taking decisions based on scientific evidence. However, teachers also need to understand the weight of evidence that is available to challenge the claims of those who use 'an expert' or 'a scientist' to bolster an entirely unscientific worldview. A critical understanding of how ideas are based on evidence requires an understanding of the processes of science, such as the use of controlled tests and the implications of sampling procedures. It also requires an understanding of why scientists do the things they do: They might repeat experiments because errors may occur at any time; they sample carefully in an attempt to eliminate bias; they present findings to peers to invite scrutiny and argument. This critical understanding of the nature of science can begin in the primary school as children carry out their own scientific enquiries.

In summary, science is a combination of the big ideas (content knowledge), doing science (procedural knowledge) and understanding the practice of science (epistemic knowledge) (for further discussion see *OECD* 2016). If 'real' science is a heady mix of intellectual and practical activity undertaken by individuals and communities then science in school should reflect this creativity, criticality and sometimes 'fuzzy' process rather than pretend science is a linear path or simple recipe for getting answers for questions. Osborne (2015) succinctly summarises teaching science as involving 'doing, talking, reading, writing and representing' (p. 18). In this book we present a view of science as a blend of thinking, doing, using skills, developing concepts and adopting attitudes that should remain intertwined during teaching. Below we will explore the theories that lead us to these conclusions.

Learning in science – some theories

In order to make decisions about how to teach we need to think about how children learn. Constructivist theories of learning and, more recently, socio-cultural views of learning have significantly influenced approaches to science education.

Constructivist theories view learning as a process by which an individual actively constructs ideas, rather than as a process of 'transmission' in which concepts or ideas are received fully formed and copied in the mind of the learner. Versions of constructivism based on the work of Piaget emphasise the importance of interaction with the physical world and see young children as behaving like scientists – making and testing hypotheses about the environment: for example, 'This toy will fall to the floor if I drop it.' In this view of learning science, the practical hands-on experiences become the most important element, and the teacher's role is to provide a rich environment for the child to explore. If we reflect on our own learning, few people would deny the power of handling objects, feeling and seeing something happen in giving us a depth of understanding. Interactionist theories such as this focus on the interaction 'between hand and mind' (Davies and Ward 2003). It is also understood that play is a vital element of learning and different kinds of play contribute to children's learning in science in different ways. Running around a woodland breaking sticks or throwing different pebbles into a pond could be defined as exploratory or *epistemic* play that results in knowledge of things. Working out how to make a swing go higher with friends in the playground might be problem-solving play and lead to an understanding of procedures for conducting other experiments. Play that involves inventing a game with rules – e.g. snail racing or hide and seek – can also lead to learning of a scientific nature.

Much of how we teach science today is founded on some 'classic' research conducted in the 1980s when science became compulsory for children in primary school. In this research there is a great deal of evidence (Driver *et al.* 1985, Science Processes and Concept Exploration Project – various authors 1989–98, see the STEM archive for Nuffield Primary Science www.stem.org.uk/elibrary/collection/3059, last accessed 21 February 2017) that when children construct their own ideas and explanations about the world their explanations are different from accepted scientific views. These are sometimes called 'alternative frameworks', sometimes less respectfully labelled as 'misconceptions'. Constructivists believe children are innately motivated to make sense of the world around them, so it is not surprising that their early attempts to explain are incomplete – they are based on very limited experiences. Realising that children are developing ideas about the world, even in the absence of being 'taught', and that their ideas are not random or thoughtless but are logical interpretations based on limited knowledge, are important insights for teachers to understand. Although not every child will construct the same ideas, resarchers have noticed that there are some common patterns in the emerging alternative frameworks, and being aware of these is useful to teachers. We outline some ways in which children think about scientific phenomena in subsequent chapters.

Social-constructivist views of learning in science (Ollerenshaw and Ritchie 1997; Harlen and Qualter 2014) also emphasise the central role of practical investigations in developing children's ideas but, in addition, they stress the importance of learning with and from others – both peers and adults. They argue that children will develop their existing ideas when they encounter new evidence, which could be in the form of new physical experiences or new ideas from other people. This new evidence may confirm or conflict with their existing ideas, or develop new ideas, but if they are not to be rejected as meaningless then children must be able to make some sense of experiences by connecting them to their existing understanding. They may be able to make links without support, or it may need the intervention of someone else to help them (a *more knowledgeable other* as Vygotsky (1978) identified). Ideas that do not make sense and that are not linked with other ideas are those that are easily forgotten.

The above theories lead us to conclude that *talking* is a vital part of learning in science and a special kind of talk is particularly valuable – where meanings are negotiated through *dialogue* (more about this below). Talk should happen among children and between children and the teacher. Teacher's questioning is important as it helps the teacher to find out what children's ideas are and to try to get at the reasoning behind those ideas. The process of talking about observations and evidence and relating it to other experiences helps to make sense of the world. In this view of learning, as well as recognising that ideas are developed within individual minds, a socio-cultural approach sets out to understand how ideas are developed *between* minds. Vygotsky (1978) proposed the existence of an individual and a 'social plane': 'intramental' and 'intermental' planes. His theory is that learning occurs when concepts developed on the social plane, the intermental plane, between people are then internalised by individuals to their 'intramental space'. Other authors (Rogoff 1990) use the term *appropriated* instead of internalised to make the point that this is an active process for the learner which transforms the ideas of the social plane, not a copying process, which would take us back to a transmission view of learning.

Socio-cultural views of learning in science also stress the importance of the cultural context for learning. In this view, the way that people interact is thought to be important. For learning to occur, there needs to be a genuine two-way process of interpretation and meaning-making, where the ideas of all participants are respected and given equal value. During this exchange the ideas of each person may develop and change. One implication of this is that teachers need to be aware of making assumptions about children's understanding of the language they use. The teacher needs to make an effort to understand children in their own terms, not just expect them to see things from the teacher's perspective. Bruner (1966) explains that to teach others we need to use our 'theory of mind' – we need to imagine what it is that another person is thinking.

Each person brings their own cultural position to the process of creating a dialogue, and this can present barriers to shared understanding. If a teacher presented putting sugar in tea as an example of dissolving, he might assume that people put sugar in a cup of tea after it was made, while in some African and Indian communities the common practice is to boil tea, sugar, water and milk together in a kettle. The scientific version of what dissolving means wouldn't change, but the way in which children made sense of the example might be different. A teacher might assume that the children understand that because they are doing science, the word 'table' is being used to refer to a chart for results, rather than a piece of furniture. Words with an everyday meaning can also have a particular scientific meaning: force, solid and fruit are further examples of this.

In the classroom the teacher has a great deal of power in determining what counts as the 'right' knowledge. Children may come to accept the 'correct' teacher's view, but not really connect it with their own deeper understandings, so it becomes compartmentalised as 'school knowledge' and kept as separate from their everyday or commonsense views of the world. Another possibility, if the teacher's view is meaningless to the child in terms of their own existing knowledge and understanding, is that they either fail to 'get it right' in school, or learn to produce the 'right answer' by rote. So, for the teacher, the art is to make scientifically accepted ideas meaningful in terms of the child's existing ideas. In order to do this, the teacher needs to understand both the child's existing constructions and the scientific body of knowledge to be taught. Implementing these ideas is clearly a challenge for any teacher. The chapters of this book attempt to support teachers in this process of examining examples of children's ideas, presenting the ideas currently held by scientists, and providing a repertoire of teaching strategies that relate them. This is not a 'top-down process': by helping children to engage with scientific ideas and language they can become part of science, rather than receivers of it. In each chapter we emphasise the importance of the context: is it interesting, meaningful and relevant? Might there be any aspects of the topic that are beyond the children's experience?

Children working together in groups without an adult present can come to a shared understanding about what they are doing and observing and how they are explaining their experiences. This can be very productive in that there is an immediate connection with existing ideas and often children can help make sense of ideas to each other in terms of a shared language and set of experiences that a teacher would not have access to. With the teacher's dominant presence removed, children are free to have a more open-ended exploration of what is taking place. However, there is no guarantee that the understandings they reach will be in line with the scientific view! There may be dominant children in the group who are persuasive and convince the others that their explanations are correct when others may have ideas that fit better with accepted ideas and evidence.

The view taken in this book is not only that scientific processes are useful in supporting children's learning, and we strongly support the importance of providing first-hand experiences and extending the evidence available to children, but also that there are a range of other strategies that can be used to create a shared understanding of scientific concepts. Different areas of the curriculum present different challenges in terms of 'bridging the gap' between children's and scientific ideas and so require different teaching strategies (Leach and Scott 2002). This includes the use of analogies, introducing scientific models and discussing vocabulary. For the teacher, this means ensuring that they and the children 'stay on the same wavelength' and they maintain a shared 'intermental space', so that new ideas can be introduced and developed in ways that are meaningful to the children – this is of central importance.

Exploring dialogic talk and learning in science

Alexander (2008) uses the term *dialogic* to express a 'genuinely reciprocal' process of communication between teacher and pupil in which ideas are developed cumulatively over sustained sequences of interactions. Using dialogic talk can support children in both understanding the scientific view and having their own viewpoints valued. Dialogic talk in which children's viewpoints are considered can be understood by contrasting it with authoritative talk in which children's ideas are only accepted if they are in line with the scientific message (Mortimer and Scott 2003):

> . . . either the teacher hears what the student has to say from the student's point of view, or the teacher hears what the student has to say only from the science point of view.
>
> (Mortimer and Scott 2003, p. 33)

Imagine if all a teacher's interactions with children were like this:

Teacher:	Can you tell me something a plant needs to stay alive?
Anna:	Water
Teacher:	Water, that's right. What else does it need?
Max:	Food.
Teacher:	Food, not really no. Plants don't eat food, they make their own. What else do they need to stay alive?
Sam:	They need air.
Teacher:	Air. Right.

This kind of interaction might be useful for a brisk recap of information, but it is not about supporting new learning and deep understanding. It also conveys the hidden message that the teacher has all the answers. It is made up of 'IRE triads'; the teacher **initiates** with a question, the child **responds**, and the teacher **evaluates** their answer.

Instead of evaluating a child's response to a question: 'Yes that's right' and moving on, teachers can use children's ideas as starting points for further discussion: *What makes you say that? Can you give me an example? What do you mean by . . .? Would anyone else like to add to that?* This helps to develop an extended discussion in which children's ideas are explored and then different contributions are linked together to build up ideas.

Learning has emotional and social dimensions as well as the cognitive elements. If the classroom provides a safe environment in which children can express their views without fear of ridicule or of them being ignored, then the teacher is more likely to be successful in eliciting their ideas and in finding out whether understanding is shared. If children are secure, they take responsibility for checking their own understanding by asking the teacher questions: 'Do you mean that . . .?', or they contribute: 'Oh yes, that's like . . .'. Children can help to explain new ideas to each other, 'You know, it's like when . . .', by accessing their shared culture in a way that teachers cannot. If the class as a whole accepts that changing your ideas is part of learning, this reduces fear of 'getting it wrong' and, at the same time, this also supports the idea that scientific knowledge is tentative and open to change. In this book we provide ideas for approaches to teaching that can help teachers to develop a culture in which questioning is valued and ideas are to be explored and developed together. The teacher plays the lead role in establishing this culture, by their example and by the ways in which they interact with children. You will find these 'open-ended' and 'person-centred' openings to dialogue suggested for each topic in Sections 2, 3 and 4.

This emphasis on dialogic talk and valuing children's ideas does not mean that the scientific ideas should not be introduced or discussed, but that this should happen in relation to the children's ideas. Mortimer and Scott (2003) suggest that teaching may involve cycles of talk in which there is a focus on exploring the children's ideas, then developing their ideas by relating them to the scientific ideas, followed by more authoritative summaries of the scientific point of view, then cycling back to a focus on the children's ideas. (See case studies 1 and 2 for examples of dialogic talk for different purposes.)

The teacher encouraged the children to respond to each other's suggestions – creating an environment in which different ideas can be considered, rather than expecting everyone to agree. There is a balance to be struck here between valuing everyone's contributions while simultaneously marking all ideas as start points that could be changed. The underlying message that needs to come across is 'We all have something to contribute and we all have something to learn'.

A feature of case study 2 that makes it dialogic is the way that children intiate lines of discussion. Clearly the relationships within the class mean they feel comfortable in expressing their ideas. The children also listen to each other's ideas and build on them. The teacher is not always asking questions, but often takes the role of choosing who will speak from the different children who have something of their own to say – much like chairing a meeting. However, she does steer the discussion in particular directions and emphasises ideas that are in line with the ones she wants the children to learn by selecting, repeating and rephrasing them. It could be described as a 'scaffolded dialogue' (Alexander 2008) – it is not open-ended, it has a clear objective, but the children's ideas and the data are used together to get there.

Case study 1
Living or non-living? Exploring children's ideas through dialogic talk

In this case study, we illustrate how the way a teacher began a topic helped to establish a class culture of open discussion and sharing of ideas. This transcript has been annotated by the class teacher and her comments are shown in italics.

I wanted to find out what the children (9–10 years old, class size 37) knew about the characteristics of living things and set our topic on plants in this broader context. The children sat on the floor in a circle around a varied collection of objects, including some living plants. Initially, we classified the collection into living and non-living and discussed some of the characteristics of living things.

The opening question was an 'invitation to participate' that had two functions. First it handed over control of the direction of the conversation to the children and second it signalled to them their ideas were going to be explored, not tested.

Teacher:	We're going to look at these things and think about whether they're living . . . whether they're non-living or anything else you've got to say about them to do with that. . . . So does anyone want to start us off? Who's got something to say? Max?
Child 1:	Well Miss, if it was living, every living thing right, it has to have something to eat or to drink to live. Say like a table for instance, is non-living because it doesn't eat, it doesn't drink.
Teacher:	So what about a plant then? (*Max has used the words eat and drink, which we usually associate with animals rather than plants.*)
Child 1:	Well down in the soil, it's got that and they eat it through the roots.
Teacher:	I see. Does anyone else want to add anything about that?
Child 2:	Sometimes you can give them food, if they haven't got enough in the soil you can give them some food. (*This indicated to me there could be a widely held idea within the class that plants get their food through their roots.*)
Teacher:	I see, you can actually buy something called plant food can't you? . . . (*Acknowledging that there was evidence to support this idea.*) Paul?
Child 3:	Well another thing about how plants live, is when we breathe out oxygen, they get it, when we breathe in . . . Carbon dioxide, they get it.
KM:	Is that the right way round? (*A number of children had appeared to be concerned about Paul's idea and I assumed I knew why.*)
Child 4:	No! No!
Teacher:	Shh I'm really glad you mentioned those two gases. (*Valuing his contribution.*) Just listen again to what you said. Donna, do you want to pick up on that*?* Not at the moment, we'll come back to you. Tom, do you?
Child 5:	Plants take in the carbon dioxide and make it into oxygen.
Teacher:	They certainly take in carbon dioxide and what they do with it, we'll think about more as we go through the term. (*Tom's response had indicated an area that would need intervention and I signalled this to them.*)

Edited extract from McMahon (2009)

The children could make distinctions between living and non-living and could identify a number of characteristics of living things. It also enabled me to identify the common alternative concept that plants get their food from the soil. Some of the children had been introduced to the idea that plants use carbon dioxide and expel oxygen, but they seemed to see it as the opposite of breathing rather than being about plants making food. Although not every child had been able to express their ideas, I had begun to build up a picture of the range of ideas held by the class.

Case study 2
Do seeds need light to germinate? Interpreting results through dialogic talk

Discussing results of scientific enquiries with children can be challenging for teachers as they need to work with the actual results they observed, the associated 'correct' scientific explanations and the children's exisitng ideas all at the same time. The intention is that this extract exemplifies some aspects of dialogic talk in science and provides a start point for reflecting on practice. This transcript has been annotated by the class teacher and her comments are shown in italics.

Dishes containing ten cress seeds on moist filter paper had been placed under transparent, translucent and opaque covers. The results showed small differences between the number of seeds that germinated in each dish. We first discussed whether we thought these differences were meaningful and decided they might just be because of the odd 'dud' seed. Then I reminded the class of the prediction we had made beforehand.

Teacher: Right just have a look at that for a moment. And think back to what we were trying to find out. Did we think it mattered how much light they had? . . . We did didn't we?

Child 1: Yes.

Teacher: What did we predict would happen, perhaps especially to the opaque one? Ellen?

Child 2: We predicted it wouldn't grow.

Teacher: We predicted that those wouldn't grow. Because we thought, well they haven't got any light so they won't grow, they won't germinate; they won't begin to grow . . . Look at those results. Is that what we found? (*Here I needed to draw the children's attention back to the data, helping them to interpret it and use it to challenge their constructs*.)

Child 3: No.

Teacher: No . . . That's not what we found at all.

Child 4: *Gasps.*

Teacher: Kate?

Child 4: It might not have been a fair test Miss. (*I was interested to hear Kate criticise the test we had carried out as a possible interpretation that would mean she wouldn't have to change her ideas.*)

The children then suggested and discussed various possible problems with the test design, for example that one container may have been close to the window.

Teacher: Mmm, it might not have been quite as accurate as we might have hoped, so that could be one explanation. Suppose it was accurate. Suppose it was a fair test. What would our results tell us? Sophie?

Child 5: That plants don't really need light that much so . . .

Teacher: That's what our experiment's telling us isn't it? That they don't need light that much to get started on growing, to germinate. (*Here, I have decided on an interpretation of the experiment that I consider to be the correct one. It might have been better if I had continued to treat it as tentative.*)

Child 6: They need water really.

Teacher: Just water?

Child 7: And food really. (*This was a missed opportunity to open a discussion on where seeds get their food.*)

Teacher: What do plants use the light for? (*This was a critical question in getting the children to apply their developing understanding of photosynthesis to explain what they had observed.*)

Child 8: *Gasp*.

Teacher: Pete?

Child 8: To make food.

Teacher: To make food. Is there any reason, why seeds when they begin germinating might not need to make food? (long pause). What do you think Carla?

Child 9: Well, I think there's some food in there, like . . .

Teacher: In where?

Child 9: Like the seed like saves, like got a bit of food, already made like water and everything.

Teacher: Sort of trapped inside the case?

Child 9: Yes.

After a few more comments from the children that showed their acceptance of this idea, Tracey, a child with a statement of special educational needs for learning difficulties, made a vital connection between real life and our experimental set up:

Teacher: Tracey, what do you want to say?

Child 10: When you plant seeds in the ground they can't get any light.

Teacher: And you're saying when, if they're planted in soil, they couldn't get any light could they? (pause) Oh, that's a thought. So, maybe, they don't need light to start growing, because, if you bury a seed underground, which you often do when you plant it, it doesn't get light. Good point. Polly, you've been waiting patiently.

Child 11: In the, haven't got leaves right . . . you can't get light, so you can't get food.

Teacher: Aahh, so it's because the leaves aren't really there yet doing their job, the seed has to have the food ready instead. That's a really good thought, I like that.

Child 12: There's no need to make food yet, because the food's in the seed.

Edited extract from McMahon (2009)

Within a constructivist-based teaching sequence this discussion serves as an *intervention* (see below), as attention is drawn to evidence that conflicts with the children's previous ideas and through the discussion an alternative idea is introduced and, after some debate, accepted. There is also evidence of application of previous learning – that plants make their own food using sunlight – to this new context of seed germination.

Pedagogy – putting theory into practice

A model of teaching science that reflects social-constructivist theories of learning in science is presented below and is summarised in Figure 1.1. We have explored this model in classrooms and with teachers over many years and developed it to take into account socio-cultural perspectives, so that learning both in groups and as individuals is considered. In the model, there are five different types of focused activity that can contribute to a teaching sequence. Although we list them below, they should not be considered a rigid 'recipe' for teaching. Teaching is a fluid and dynamic process and cannot be captured in any one model.

Orientation

Perhaps the most important part of any teaching is getting the lesson underway in a positive, engaging way. Piagetian principles (Slavin 2005) that inform constructivist and 'child-centred' education include the recognition of the crucial role of children's self-initiated, active involvement in learning activities. In its purest form, to be 'child-centred' means to encourage children to discover themselves through spontaneous interaction with

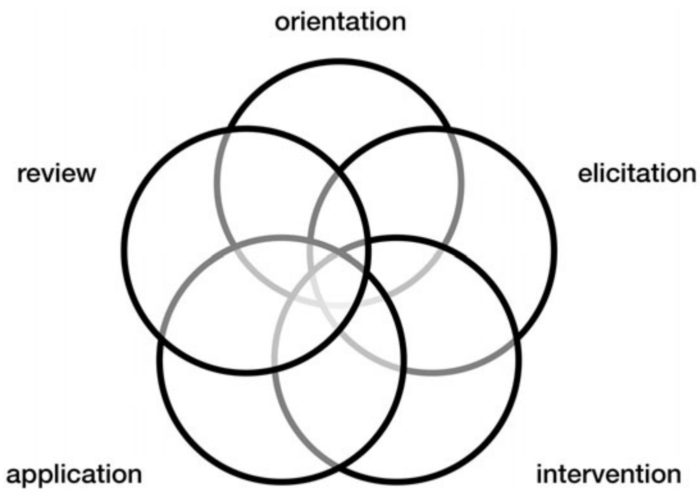

FIGURE 1.1 The constructivist teaching typology

the environment. However, teachers are also required to teach a prescribed curriculum, so they are faced with the challenge of 'delivering' material and engaging children with topics that do not arise 'spontaneously'. Skillful teachers will capture attention and the curiosity of their pupils and begin to motivate them to learn. In this model teaching sequence 'orientation' acknowledges that a process of introduction, setting the scene, of putting the topic into a context and of engaging the children's interest is needed. It is a regular part of most primary classroom practice in many subjects and is likely to involve the whole class. Orientation involves a provocation for learning that the teacher introduces; reading a story, exploring a collection or discussing a local event or it might be a response to something that the children have initiated. There are opportunities for talk as children share their perspectives on a topic or relate it to their interests. One challenge here for the teacher is to be mindful of the objectives they have for the scientific learning and choose their questions carefully, so that the discussions don't stray too far – children are experts at 'side-tracking' any discussion. The class as a whole can benefit from the breadth of ideas and questions that different children might bring. In a topic called 'Clothes we wear' (planned to address understanding of properties of materials) children could watch a short video clip of children doing an activity such as riding a bike and be asked what activities they enjoy and what clothes they would wear to do it. They could discuss the clothes they are wearing to school and think about why different clothes are worn for different purposes. Children do like to feel part of things, that they have something to contribute, and that the topic is meaningful for them. Planning a thoughtful orientation with time for the children to respond by talking together can help to establish a shared commitment to the topic for the class.

Elicitation

Orientation often merges into 'elicitation'. Elicitation is a powerful process of clarifying and finding out the children's existing ideas. Essentially, this is a process of assessment (more of this below), which is seen as an integral part of constructivist learning. In 1968 an eminent psychologist David Ausubel wrote:

> The most important single factor influencing learning is what the learner already knows. Ascertain this and teach him accordingly.
>
> (Ausubel, 1968, p. vi)

This famous quote has influenced science educators and researchers ever since. For the twenty-first-century teacher this means gaining an insight into the child's current understanding of the concept(s), so as to adapt their teaching. For the child, it is a process of becoming aware of their own ideas, of making them tangible, of 'structuring' them; this is the start of developing and possibly changing their ideas. We have seen above how thought and talk are closely associated. Through talking and (importantly) listening, children may begin to be aware that others have somewhat different ideas or that they cannot explain something to their own satisfaction. Recording these ideas may be part of the process of clarifying them, and may be useful for both teacher and children to reflect on later. Different topic areas lend themselves to different ways of finding out and recording children's existing ideas, and these are known in science education as 'elicitation strategies'. In Section 5 you will find them discussed in detail.

Eliciting children's ideas is important at the start of a topic or unit of work as it can then inform medium-term planning for the class as a whole and identify groups or individuals who may need additional support or extension. However, it is not only for the start of the topic: it is important that teachers continue to provide children with opportunities to express their developing knowledge, and the elicitation strategies can be used at any point as part of formative assessment. They can also be used at the end of a topic so the children can think about what they have learned. In this way, the elicitation is linked with review. Reviewing can take place at any point in a teaching sequence; it is a good idea to build in frequent opportunities for children to reflect on their ideas. In this book we support the use of elicitation strategies to help teachers gain insights into children's minds as an integral and ongoing part of their practice, rather than a one off event at the start of a topic.

By seeing elicitation as a collaborative rather than solely individual activity, a variety of ideas and views are made available on the social plane of the classroom for children to consider. The process of elicitation can be seen as creating a shared pool of different ideas and experiences providing a rich starting point for everyone to learn from. Owning a range of ideas as a class might enable those ideas to be examined more critically – it is not a person being examined – it is the idea.

In each chapter we explore a relevant elicitation strategy, or strategies, and exemplify it (them). Many of the strategies can usefully be applied in a range of conceptual areas but, by exploring the benefits of each elicitation strategy for certain purposes, we hope that teachers will be able to make informed choices about which to use when.

Intervention

Having elicited children's ideas, the teacher can then decide how to help move the children's understanding forwards. Of course, different children in the class will have different starting points, and meeting the needs of the whole class can be quite challenging. Some may need to extend and develop existing ideas; others may have alternative ideas that need to be challenged and significantly restructured. Sometimes children's alternative ideas can be very resistant to change, as they keep hold of ideas that make sense to them, and a range of different teaching strategies may be needed to help the children learn the scientific version. The word intervention emphasises that this is an active process for the teacher, requiring careful analysis of the children's ideas and selection of appropriate kinds of activities.

In a social-constructivist approach the most important intervention is to encourage children to test their ideas through the processes of scientific enquiry to extend, develop or replace them. This is not suggesting that children can 'discover' what has taken thousands of years of experimentation and thinking. The role of the teacher is crucial in helping to identify productive lines of enquiry and in making sure that children understand the relationship between their own ideas and any activities. In order to do this the teacher needs not only to know what the child's ideas are, but also to have an understanding of the thinking behind them. A child may say that a toy car eventually stops rolling along the floor because it has 'run out of energy', and then through exploring how different surfaces affect how the car travels, develop their understanding of the role of friction in slowing the car down.

Taking a socio-cultural view, the process of restructuring could be seen as a collaborative gathering of relevant experience and sources of evidence and a communal evalaution of the possibilities. It mirrors a view of scientists, not as brilliant loners, but as a community with a collective responsibility to criticise each other's interpretations of data, to look for exceptions to rules and to find the best possible explanations.

Other forms of intervention do not directly involve scientific enquiries. Ideas may be based on colloquial use of language such as a sign on a shop door saying 'No animals allowed here'. Discussion about what people mean by the term animal would be helpful in this case. Ideas may be based on limited experience, for example 'our food goes into our tummies and then into our arms and legs' in which case evidence such as models and drawings of what is inside our bodies and alternative ideas about what happens to food could be introduced. Challenges to existing ideas might come from various sources: other children, books, videos, visits, visitors or the teacher – *'The way I see it is that . . . Does that make any sense to you?'* The use of models and analogies can be very helpful in discussing ideas that are not immediately accessible to children.

Practical work may not always be in the form of a full investigation (see Table 1.1 for a summary of alternatives). Teachers can plan activities with a purpose in mind. For example, first-hand observation of their teeth might be combined with the teacher raising a question about why food needs to be broken into smaller bits. Children might go on to research different kinds of teeth (Do birds have teeth? Are snake fangs teeth? Has everyone still got their baby teeth?).

Application

Children need to use new ideas in different contexts in order to take ownership of them and to be secure in their understanding of them. Also they need to see the value of the new ideas or they are likely to revert to previously useful ways of thinking. Opportunities for this may come through cross-curricular work. Designing and making provides many opportunities to apply scientific ideas. Children can be presented with problems to solve using their new understanding, such as working out how to separate out rubbish for recycling using their knowledge of the properties of materials or how to create a shadow-puppet show. Sometimes ideas developed in one science topic can be applied in another – a child might draw on their understanding from a topic on light to suggest using transparent, translucent and opaque materials to cover germinating seedlings to test the effect of different amounts of light on how they germinate. A class culture that values children's ideas and sees them as relevant can also help them to make connections between ideas rather than compartmentalise different aspects of their learning.

Review

Reviewing is sometimes seen as what is done at the end of an activity, but can be a much more continuous process. A better way of seeing review might be as part of the ongoing dialogue with and between children about their ideas. This thinking about thinking, or metacognition, is an important theme of other approaches to learning in science such as CASE (an acronym for Cognitive Acceleration in Science Education – more details in Section 3).

In science children can both think about how their ideas might be different now from ones they held previously, and how the change in their ideas came about. '*I used to think this and now I think this because . . .*' Teachers might also talk about what they have learned. This is an important time for teachers to help children make the link between ideas and evidence and how scientific knowledge is continually changing. Part of progression in learning science is moving from personal knowledge to a shared knowledge. The process of reviewing ideas collectively enables the class to decide which ideas are thought to be particularly significant and give them the special status of shared knowledge. However, time for individuals to reflect on their personal learning is also important.

Constructivism – a critical examination

> The most conspicuous psychological influence on curriculum thinking in science since 1980 has been the constructivist view of learning.
>
> (Fensham 1992, p. 801)

> Constructivism has become increasingly popular . . . in the past ten years. . . . it represents a paradigm change in science education.
>
> (Tobin 1993, p. ix)

Undoubtedly, theories that draw on 'constructivism' have hugely influenced science education in the UK and around the world. Almost as soon as science education began to be influenced by these ideas that emerged from psychology cognitive learning theory, there have been debates about its relevance and usefulness. It has been argued (Matthews 1998) that constructivism necessarily involves considerations of philosophy because the consideration of how new and valid knowledge is generated is an epistemological one. Furthermore, there are many varieties of constructivism – educational, sociological, philosophical, each associated with different perspectives and stances – but science educators have not resolved some deep questions about the validity of claims made. We can't go into the nuanced and complex arguments in this book, but do wish to alert the reader that the 'pedagogical constructivism' that we explore here has it critics and indeed ought to be challenged. The central questions that Matthews and many others since have posed is this: How can we reconcile the notion of enabling and permitting children to explore their own ideas and come to their own conclusions (because we believe knowledge is constructed by the individual) when those conclusions may be erroneous or very different to the established body of scientific knowledge (which exists independent of the individual)? Is it not true that at some point, teachers will have to tell children the right answers? Is to pretend otherwise to put teachers in an impossible situation? These questions arise because there is arguably an erroneous connect between two fields of study – epistemology and psychology – that understand constructivism in differing ways. Matthews (1998) believes educators largely ignore the deeper issues and mistakenly continue to promote 'constructivist teaching'. The debate still rages in academic circles but we cannot ignore the fact that educators still find constructivism to be a powerful guide to pedagogy. What we do not advocate in this book is what might be described as 'minimal instruction' or 'discovery learning' where the teacher's main role is to stand back and watch children learn. Constructivist pedagogy values 'hands-on experience' but that does not mean that scientific concepts emerge neatly and inevitably from those experiences; there is a difference between first-hand experience of phenomena and the human explanations for it. Often the human explanations involve an act of imagination. For example, children might be able to see that sugar dissolves faster in warm than cold water, but the reason for this does not emerge from the practical enquiry. The human interpretations and explanations can only be found through social and cultural interactions – with people, books, the internet and so on. We do recognise that a teacher has many roles during teaching and we discuss these throughout. We have already highlighted the importance of talk. It is during discussion, questioning and dialogue that teachers should challenge children's thinking, present relevant evidence to them and promote critical thinking.

An important question to ask is, 'Does teaching according to constructivist principles actually work?' It is a difficult question to answer as teaching is such a complex and nuanced process. The short answer might be, 'We think so but can't be sure.' There is certainly a wealth of research published that suggests that it is an effective approach. As food for thought, consider science education in Hong Kong. The region does exceptionally well in international comparisons known as 'PISA' (the Programme for International Student Assessment). In scientific literacy, Hong Kong's ranking has progressed from third in PISA 2009 to second in PISA 2012, with the performance of students improving steadily. The Hong Kong Government (Hong Kong Education Board 2013) argue that:

> the good performance of Hong Kong students in science confirms the appropriateness of the Science Education curriculum which emphasises scientific literacy and generic skills (e.g. critical thinking and problem-solving skills). The curriculum, which has been reviewed and revamped in the curriculum reform, assists teachers to adopt appropriate classroom strategies to enhance students' understanding of science knowledge and development of process skills through scientific investigation, as well as strengthen their understanding of the interconnection of science, technology, society and the environment.
>
> (press release)

In the associated curriculum documents produced by Hong Kong's education department, (Hong Kong Curriculum Development Council 2002) their guidance asks that:

> Learning of science should centre on scientific investigation and move away from 'recipe' approach. Students should develop understanding of scientific concepts . . . The organization of learning experiences should start from where the students are at, utilize their background knowledge, set a context which they perceive to

> be relevant, and build upon their experience and understandings, so that students could put together conceptual frameworks of their own and develop their own understanding of the world around them. Students should learn how to plan and take control of their own learning.
>
> (p iv)

Statements that relate to 'construction' of knowledge, meaning or theories appear throughout the 100-page document. It is clear that science education in Hong Kong is heavily influenced by the constructivist theories that we have debated and discussed here. It is also clear that science education in Hong Kong is very effective, at least in the outcomes measured by PISA. What is not clear is the 'cause and effect' connection between the two. We will leave the reader to ponder the questions that this raises.

Assessment

Assessment is an integral part of learning and teaching and will be discussed and exemplified throughout this book. There has been considerable research, discussion and debate about assessment in the education world for many years. There has been much written about the meanings of and relationship between *summative* and *formative* assessment. In this book we take the view that our focus should be on the purposes of assessment. In the design and carrying out of assessments we should always bear in mind these questions: 'Why are we assessing?', 'What are we going to do with the information gained', 'What will the impact of assessment be on the learner?'

Assessment comes in many forms: tests, quizzes, discussion, observations, practical tasks, group work, presentations and so on. It can be carried out during everyday classroom activity (teacher assessment) or by conducting externally prepared testing (such as national tests or exams). Teacher assessment could have either summative or formative purposes. For example, a quiz could be used at the end of a unit of work to 'sum up' the knowledge a child has retained from a month of science learning. The same quiz could be used at the start of a unit with a class to elicit the knowledge across the class on a new topic and inform a teacher's subsequent plans and approaches to further classwork (also known as *Assessment for Learning* (AfL)). We have already seen how 'elicitation' and 'review' are closely related processes by which children's knowledge and understanding are explored at different points in a teaching sequence.

We can view teacher assessment as a process that begins with the collection of data or evidence. As a teacher interacts with her pupils, she will gather information about what they say, what they can do, how much help they need, where they are struggling, what they can explain with ease. These data are usually stored either in the head of the teacher or elsewhere – in the child's book, in a notebook, in electronic form as text, photos, video or sound clips. Of course not everything a child says, does, draws or writes will be stored or captured. In most cases, this will rely upon teachers' professional judgement. We will discuss throughout the book some of the strategies that teachers use to catch significant moments. The next phase of the process is to examine the data for useful information. Again, professional judgement is required, although it also may involve the judgement of colleagues and of the children themselves. In all