3RD EDITION

EXPLAINING PRIMARY SCIENCE

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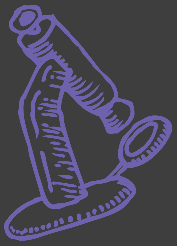
INTRODUCTION: TEACHING PRIMARY SCIENCE TODAY



'I TOUCH THE FUTURE. I TEACH.'

Christa McAuliffe, NASA Astronaut

It is crucially important that we teach science in primary schools, and that we teach it effectively.

Twenty-first-century citizens are surrounded by the impact of science, its benefits and challenges. Science extends and enriches our lives by providing access to clean water, nutritious food and targeted medication. Those technological innovations, which have appeared exponentially since the start of the industrial age, extend the range of human experience, exploiting endless mechanical, chemical and electrical applications. Science encompasses humanity's greatest achievements by creating new knowledge and benefitting society by improving the quality of our lives. While threats to the planet, such as climate change, ocean health, biodiversity reduction, pollution, overpopulation and the emergence of novel virus variants, can be explained by science, it is people, not science, that create the problems.

Science raises questions and seeks answers. Debate fuels scientists' discussions in order to refine theories.

Almost every country recognises the economic importance of STEM (science, technology, engineering and mathematics). Expressing a desire for young people to be exposed to the nature of science and technology, politicians direct their main concerns towards numeracy and literacy standards. Changing curricula and continual scientific and technological advances make it difficult for the population, including primary teachers, to remain informed of contemporary advances.

Science is dynamic. Its priorities respond to societal needs and global challenges. Engagement with science is essential for equipping citizens to make informed choices. Teachers are twenty-first-century citizens who are surrounded by scientific processes, media messages and artefacts. Their personal and professional identities include being members of a scientific society. Above all, their capacity to learn and promote learning characterises their expertise.

'Science Happens Here' might be a worthwhile message to hang on the school gate.

This text is designed to assist student teachers and practising teachers in their planning, preparation and delivery of the science curriculum. It has not focused on one country's curriculum but has synthesised the key aspects of a broad science experience, which will provide practitioners with confidence in their scientific knowledge and abilities to design and deliver a rewarding scientific experience for their pupils.

Using this book

Explaining Primary Science (3rd edn) sets out to support the planning and delivery of high-quality science teaching and learning during primary schooling.

Our ambitions are to provide teachers with insights into science, its teaching and approaches. The pace of global innovation is such that neither curriculum nor teaching resources can provide comprehensive, current coverage. We anticipate that the book will be used in a variety of ways. Trainee teachers may use it to support them during the first phase of their career, employing it to shape their personal, professional journey. Experienced teachers might be more selective, searching for appropriate inclusions during lesson preparation for their programmes of study. We aspire towards providing a resource that will shape and assist teachers' practice and continuing professional development (CPD).

The literature describing teachers' attitudes to science in the early stages states they aim to deliver innovative and motivating experiences in science but that they lack the confidence and background knowledge. Additionally, the structure and organisation of their institutions may not be conducive to developing their skills in this area.

Following the introductory overview, the advice we give in the chapters in this book is organised around three content-related sections.

Chapters 1–7 provide a starting point for the study of the life sciences. They are additionally connected to, and dependent upon, other fields of study, notably social studies' emphasis on the physical and human environment and links to health, personal and social education, and citizenship education.

Contemporary life sciences are an extraordinarily varied group of subjects that often call on the disciplines of all areas of science. Traditional biology that relied on observational and anatomical studies, has been replaced by enquiry that brings together techniques of other sciences, enabling previously unimagined scientific insights. Subjects studied in detail extend literally throughout the alphabet from anatomy to zoology. One consequence of the scientific advances in the life sciences is public concern over social, moral and economic issues such as biodiversity, vaccination, global warming, food quality and genetic modification.

Chapters 8–12 relate to the physical science topics around matter and its properties. These incorporate the states of matter, how we believe it to be structured and ways in which humans have used and adapted these properties for our benefit. The chapters include the structure of the Earth, what we believe its composition to be and how we can extract materials that we require for our sustained existence. The chapters link to geology, tectonics and the environment. The impact we are having on water supplies and its use are discussed not only in terms of the science but also in a sustainable context. There are related links to conservation and use of supplies in the future.

Chapters 13–19 outline the fundamental principles of forces, energy and its behaviour and the structure of the universe and solar system. Historically, these areas have been described as problematic in primary school due to the so-called 'abstract' concepts involved. These chapters attempt to explain the underlying concepts but also suggest ways in which we can reduce the opportunity for children to form misconceptions. The use of consistent terminology and simple descriptive solutions to the experimental results should allow teachers to approach these topics with confidence.

The world is children's laboratory and we encourage you to exploit this at every opportunity. The desired intention is that the text will give you the knowledge and confidence to practise scientific enquiry whenever the situation arises. Do not stop following a line of interest. When children ask questions, we are well on the way to promoting curiosity and a lifelong search for answers as well as asking new questions. Science does not need to be restricted to formal activities that happen in the classroom, home and outdoors. We do science anywhere, anytime.

The remainder of this introduction offers an overview of key issues relating to the teaching of science, in order to provide a wider context for the subject-knowledge-focused chapters that comprise the book.

Science in a wider context

Science is …? A chameleon perhaps, since its appearance changes with perspective. Politicians, economists, scientists, learners and consumers view the content, process and challenges that science brings in many ways. These views influence the appearance of science and what drives science education.

Humans embrace science in many ways – perhaps. Perhaps as opportunities or threats, triumphs or challenges, depending on personal beliefs, attitudes and values. The learning journey starts in early childhood. Questions about our surroundings, comfort and future litter early childhood. Progress through all stages of education is complemented by the insights gained informally through the home environment, the media and the full impact of the internet-driven information age. The scope and range of contemporary scientific enquiry extends from the furthest reaches of the cosmos to the nature of matter from which we are constructed.

Curiosity lies at the heart of our psyche. Understanding is shaped by our environment and all its complexity. Those questions we asked as children remain at the heart of scientific enquiry, with additional compulsion to provide explanations – upon which further explanation might be based. Such enquiry is never-ending. As renowned cosmologist Professor Carlos Frenk notes: 'Science is hard and science is challenging, and science is full of failure' (*Desert Island Discs*, 2018). Yet science is rewarding in terms of learning, teaching, understanding and twenty-first-century citizenship.

Science, its development and its potential to contribute to national economies, is a political priority throughout the world. Science education is viewed as the route by which nations imagine they can gain a larger slice of the global economies that are derived from science. Such ambitions are global across the political and geographical spectrum. A rigorous grounding in STEM is viewed as providing competitive advantages and economic, employment and social benefits.

There are many 'sciences' with countless in-depth studies across the entire spectrum of human experience. Within those specialisms, the content, context, skills, behaviours and targets are varied, while all seek to validate scientific findings. The Science Council (n.d.) provides a useful definition that encompasses the nature and practice of science:

> Science is the pursuit and application of knowledge and understanding of the natural and social world following a systematic methodology based on evidence.

Practical and theoretical science is rehearsed throughout this book. Children's experiments and investigations provide challenging, robust science education and are the basis of good science.

We have adopted investigative approaches in many of the suggested activities. The process 'Think, do and think again' summarises the phases of an investigation. Science depends on careful observations, on making comparisons 'before and after' and recording those changes. We then attempt to create general rules as to what might happen in subsequent situations. Findings require us to be tentative in the creation of those rules, sceptical about new ideas and to provide generalisations of the world about us.

The integrity of science is built on previous knowledge, systematic study, that can be replicated and provide new explanations, which in turn can be confirmed by others in order to make predictions towards further study.

Children's learning

Science in primary school aims to build on what children already know and to incorporate approaches that support what they want to know. Conventionally, thinking and reasoning are developed in science lessons within a constructivist approach. Acknowledgement that ages and stages contribute to children's cognitive development and a belief that learning should be active lie at the heart of constructivist philosophy.

Children's learning is influenced by an extraordinary range of intrinsic and extrinsic factors. Their learning evolves through modification and refinement of their ideas. Malcolm Swan (2001: 154) asserted, 'misconception is not wrong thinking but it is a concept in embryo or a local generalisation that the student has made. It may in fact be a natural stage of development.' Each journey is unique to the individual. Capitalise on their capacity to invent rules and explanations. Learning can be assisted by the challenging, not dismissive questions 'What if we ... ?', 'What might ... ?'

Children must be given first-hand experiences, be provided with opportunities for making errors, and be exposed to information in a way that can assist problem solving. The activities related to learning should be presented in meaningful contexts rather than abstract exercises.

The title of Kimber Hershberger's 2018 blog entry 'Science class: a place where children should be seen and heard' is eye-catching and provocative. It might be regarded as a clarion call for learning and teaching in science, STEM and all curriculum areas.

The curriculum

Amongst the many purposes of education, we might find reference to providing children with cognitive resources progressively to make increasing sense of their enquiry. Throughout the world, the formal curriculum supplies approaches to assisting systematic study in science in collecting data, organising findings and recording these in ways that can be shared with others. Advanced learning involves the identification of problems and their resolution. Enquiry and science involve more, much more than this.

Curricula are designed to provide 'balance'. The best intentions are towards providing a range of experiences, contexts and coherence National curricula supply structures within which effective learning is prescribed. The greatest sin in their design is that it lays the route to establishing those monsters called 'subjects', justified as preparation for the secondary stages. Once established, those subjects become the source of comparison, preferences and prejudice. The relationships and conceptual bridges between subjects become confused and lost. Boundaries are built and the learner risks failing to exploit, for example, a numerical skill within a historical activity or apply creativity beyond an artistic setting. Learning does not take place in convenient compartments. Nor does science. A raft of interdisciplinary skills is required in its execution, whether by an individual during the earliest years, or within the most advanced research team.

Countries determine their own curricula based upon their national heritage and culture. The actual 'teaching content' is remarkably similar across the globe in that basic science is universal (consider, for example, the similarities in the English and

Scottish primary science curricula maps included as appendices in this book). The curriculum in its entirety is designed to produce the type of citizens each country wants. It is the combination of all the subjects and their various skills and knowledge that is taught within it that provides the environment that nurtures young people. Primary teachers have a difficult role. They must be knowledgeable across all areas. This introduction, 'Teaching Primary Science Today', is designed to assist teachers in this context.

While curricula change, science remains.

Primary science teaching today

The current state of science teaching in primary schools is the subject of ongoing scrutiny. The Primary Science Teaching Trust's rationale is aspirational towards the future. They suggest on their home page: 'While not all children will follow a career in science or related disciplines, science literacy will influence their lives daily: for example, in managing their health, and understanding issues such as climate change. Science taught in primary schools is therefore of vital importance both to individuals' and nations' well-being.'

The Wellcome Trust previously (2014) asserted that invigorating and championing primary science required actions from individuals and school leaders in both CPD and budgetary considerations.

The reasons for teachers in primary schools lacking confidence are complex. These might be brought about by weaknesses in initial teacher education, where the focus has been on more broad educational issues rather than subject-specific input, a lack of appropriate CPD, a gender imbalance as well as a 'cannot do' staffroom culture.

While teachers might express a lack of confidence about teaching aspects of science and other parts of STEM subjects, a dilemma exists between that position and that of being a citizen of the twenty-first century. That lack of confidence might be redirected towards the professional abilities associated with a capacity to learn, an acceptance that personal knowledge is finite and that process skills facilitate enquiry pathways. Teachers' understanding will necessarily be different from their charges'. If providing knowledge is regarded as a disposable commodity then its significance is diminished within learning pathways. Teachers should not feel compromised about providing an answer, or indeed knowing 'the answer', at risk of breaking children's sense of wonder.

Teachers' understanding and confidence are derived from the capacity to facilitate learning by developing coherent pedagogies that incorporate enquiry types and skills. Inevitably, significant barriers exist that obstruct raising teachers' confidence – time, resources, health and safety.

Being scientific

While professional scientists are normal people who are in possession of special skills, we believe that the scientific capability of the general public exists at a high level due in part to our immersion as twenty-first-century citizens. You can be aware of your own scientific capacity by considering the following points:

- reflect on the number of science-based questions that arise in a television quiz (and how many you can answer);
- audit the number of science items contained within a daily newspaper or broadcast report;
- consider the problem-solving routines that you exercise to resolve domestic electrical or electronic faults;
- have you expressed views on issues such as renewable energy, climate change, plastics in the ocean?

You will quickly realise that you possess extensive scientific knowledge, skills and attitudes. These are the product of your own education and life today. As part of your everyday life, you act rationally and scientifically.

Children are driven by curiosity and exploration. Schooling and education supply the cognitive resources to make sense of their enquiry. Schools provide order, structure and discipline that facilitate collecting data, making sense of it and communicating ideas. Systematic study and the development of insights describe all learning, irrespective of content or context. Intelligence involves the identification of problems and finding solutions. Children can be scientific and teachers' roles are to help them act scientifically.

Scientific vocabulary and literacy

How do we teach our children to express clearly what they have learned? With young people, the meaning of what they talk and write about may be limited by their vocabulary. In particular, when describing or discussing an issue their true meaning(s) may be unclear due to the words they choose. As part of our teaching, we progressively introduce them to more and more scientific vocabulary. This book proposes that you teach the 'scientific' meaning of the terms and encourage children to use the specific meaning of that term when describing what they have observed. We also advise that the children are encouraged to use, describe, discuss and argue as frequently as possible. The language they use will initially be theirs and should progress towards using precise scientific terms. The aspiration is that if we can enable children to use the terms regularly, they will become part of their standard vocabulary, thereby embedding the underlying concepts. Once that is established, they can build on this to extend their understanding. That is, they will use the terms they have as part of their vocabulary in other unfamiliar situations. This links to ideas around social capital in that the young people can be involved in discussion around not just localised matters but also about ‘academic’ topics. This can increase their social capital but also push them towards being more scientifically literate. With a greater knowledge of scientific vocabulary and an increased scientific literacy, they can more easily and knowledgeably navigate the ideas around a topic and comment critically on its validity. These ideas are closely linked to the concept of ‘scientific capital’. This concept is gaining momentum in the research environment and is informing practice. Science capital is viewed as encompassing a student’s science-related values, thereby linking their scientific knowledge, skills and attitudes to relevance in their everyday life. Research carried out by University College London, King’s College London and the Enterprising Science Project has provided insight into why and how individuals engage with STEM-related experiences. Positive experiences can contribute to the quality of the individual’s learning and have the potential to influence perceptions towards STEM and the underlying science capital.

Much recent attention has, rightly, been given to extending discussions around and commitment towards scientific literacy to include the full range of STEM. Such thinking arises from considerations raising the profile of the STEM subjects and in many areas contributing to perceived economic gains. STEM literacy is the ability to apply concepts from science, technology, engineering and mathematics to solve problems that cannot be solved using a single discipline (Jackson et al., 2021). Coordinating STEM subjects, science, technology, engineering and mathematics, enables teachers to facilitate improved student understanding of the world today. The National Science and Technology Council (2018: 1) validated STEM, determining that ‘modern STEM education imparts not only skills such as critical thinking, problem solving, higher order thinking, design, and inference, but also behavioural competencies such as perseverance, adaptability, cooperation, organization, and responsibility’.

Scientific theories

It is worth pausing to contrast what is meant by theories in science as compared with common usage. The *Oxford English Dictionary* gives a range of definitions but the interpretations below highlight the difference between scientific and more common usage:

- *Theory, Sense 1*: An explanation of a phenomenon arrived at through examination and contemplation of the relevant facts; a statement of one or more laws or principles which are generally held as describing an essential property of something.
- A hypothesis that has been confirmed or established by observation or experiment, and is propounded or accepted as accounting for known facts.

As Richard Feynman said: 'It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong.'

- *Theory, Sense 2*: A hypothesis proposed as an explanation; hence a mere hypothesis, speculation, conjecture.

This implies that the theory is speculative, not proven. Creationists often argue that evolution is just a theory. The phrase 'in theory' is often used in this context but as a preface to contradicting something or just guessing. For example, 'In theory this should work, but it doesn't …' or 'I have a theory as to why we lost that match …'.

This text focuses on scientific theories. Theories in science are widely accepted by scientists as they have been substantiated and confirmed through repeated observations and experiments. Examples include 'the Big Bang theory', 'atomic theory', 'chaos theory', 'cell theory' and 'evolutionary theory'. Such theories allow scientists to make explanations of observed phenomena as well as predictions about experimental outcomes. On the other hand, common usage suggests that theories involve speculation and guessing. This dichotomy may lie at the heart of some conceptual difficulties.

Scientific theories do create dilemmas for teachers since detailed explanations frequently lie outwith concrete experiences and also children's developmental stages. For example, while we can detect the change on the brightness of a bulb when we add new batteries to a torch, we are unable to quantify this in terms of the voltage applied to the lamp. To link the brightness to the voltage across the lamp quantitatively, we would need to connect it to a voltmeter. Atomic theory lies behind our understanding of chemical reactions, yet we are unable to see atoms and their interactions and constituents without sophisticated technology and resources. Big Bang theory is possibly an unhelpful term. It implies there was one 'Big Bang' but scientists would more likely refer to this as an 'event'. As we are observing the structure of the universe some 13.8 billion years after the event, we have no direct evidence of what occurred. However, the gradual collection of data, testing and debating hypotheses, and supporting and/or refuting these have progressively refined our knowledge, leading to our current understanding. The theory on the origin of the universe is not an act of simple speculation, it is the result of hundreds of years of scientific enquiry. When referring to a theory in this text, we are referring to tried-and-tested scientific theories.

Controversy and scepticism in science

As people, we will not always agree with one other. We might prefer different food from our friends; support a different team; enjoy different music; or have different viewpoints on political issues. We may even voice our disagreement with our peers occasionally. Disagreeing is not necessarily being controversial. Being 'controversial' involves much more than simply disagreeing or expressing a matter of opinion. Being controversial is generally stating something that is almost certainly going to lead to disagreement or debate. How we deal with or encourage this debate is part of the nature of science.

Scientists work in particular ways to test their theories in order to confirm their hypotheses. This involves seeking evidence to support the case and publicly debating it over a long period. Journals will only publish scientists' findings following scrutiny by other scientists, their peers. Such 'peer review' and debate around published research continues to challenge scientific understanding.

Controversy in science occurs when scientists disagree about, for example, the methodology or validity of the conclusions. Peer review is an essential part of the way that science progresses. It is through the interpretation of evidence and the discussion and debate about meaning that we develop knowledge and understanding. Teaching children how scientists work to refine facts will make them less likely to be misled. Critical skills can be encouraged by, for example, looking at fake news, plagiarism, the authenticity of data sources and the credibility of experts as part of science and general education.

The nature of science

> Science is a way to teach how something gets to be known, what is not known, to what extent things are known (for nothing is known absolutely), how to handle doubt and uncertainty, what the rules of evidence are, how to think about things so that judgements can be made, how to distinguish truth from fraud and from show.
>
> Richard Feynman, Nobel Laureate

Scientific knowledge is supported by evidence. However, when new techniques or processes become available and ideas are constantly tested, then new knowledge will emerge to replace the existing ideas. For this reason, *all* scientific knowledge is regarded as being tentative.

Scientific knowledge is built upon facts, hypotheses and theories. Scientists regard facts as things which are known to be true. A hypothesis is a statement that takes into account previous observations which can then be scientifically tested to determine if it is true or not. Theories in science are widely accepted ideas or constructs that help to make sense of related observations and experiments.

Scientific methods involve many different approaches. Scientists work individually or within teams; they test hypotheses; generate different forms of data; repeat their experiments; reach conclusions; and take part in the peer review process. There really is no single way of working or scientific method.

It should be clear that an essential part of being scientific involves constantly challenging new scientific findings and established 'facts'. Scientific journals are full of correspondence where controversy appears when scientists debate different viewpoints.

You would think with all the publicity in the press and social media that topics such as evolution by natural selection, animal testing, nuclear power and climate change would be controversial among scientists, but that is not the case. Evidence to support Charles Darwin's ideas about evolution by natural selection is drawn from all areas of biology and contributes to their progress. The science is accepted; it is not controversial.

Scientists do not rate animal testing as being controversial. One study reported that 'more than nine-in-ten scientists (93%) favour the use of animals in scientific research, but only about half of the public (52%) agrees' (Pew Research Center, 2009: 5). Once again, the science is accepted; it is not controversial. Animal testing is carefully regulated by governments. More than 500 distinguished UK scientists, including three Nobel prizewinners and 250 university professors, have pledged their support for animal testing in medical research:

> Throughout the world people enjoy a better quality of life because of advances made possible through medical research and the development of new medicines and other treatments. A small but vital part of that work involves the use of animals.
>
> Research Defence Society, 2007: 3

Scientists are also more in favour of nuclear power than the general public, and while nuclear accidents have caused shocking results, it should be noted that many, many more people die from the effects of air pollution each year or working in the coal industry, for example. Again, the science is accepted; it is not controversial.

Climate change is another area where scientists accept that this has been brought about by human behaviour – the science is accepted; it is not controversial. *The New York Times* reported on 10 January 2023 that the previous eight years had been the hottest on record (Fountain and Rojanasakul, 2023). Those are the facts. What has caused this is still under debate; its consequences are the subject of speculation and further discourse. This increase in temperature has been linked to rising CO_2 levels in the atmosphere.

There is a correlation but it may not be causal. This allows debate and discussion around the issue. This is where scientific controversy is found.

Vaccination is not controversial. Successful vaccination provides protection against pathogens by mobilising the body's immune response to combat infection. Vaccination results in the eradication of certain diseases and saves many lives. Vaccines protect us from dreadful, debilitating and fatal diseases. Similarly, the development and administration of vaccines provide continued protection against the SARS-CoV-2 coronavirus, the cause of the Covid-19 global pandemic. This is a fact. While risks are inherent in all treatments, the overwhelming fact is that vaccination saves millions of lives.

It must be true – it was in the news!

Keep your wits about you on April 1st! Newspapers frequently provide stories that appear to be true, but they are being humorous and simply trying to fool you. Other 'news' might have more cynical purposes, and skills are required to consider the authenticity of the assertions contained within reports. How can we evaluate the accuracy of a report? There are some simple initial checks that can be undertaken. For example:

- Ensure students read the article or watch the programme closely.
- Check that it has a direct identifiable source, or is it 'an observer stated …'?
- Was the incident reported by other bodies such as reliable national news agencies or a university?

It must be true – I saw a science documentary!

Sadly, scientific documentaries that purport to relate current scientific knowledge or research are being marginalised. Many 'scientific' documentaries or channels no longer adhere strictly to the science. They use conjecture with computer-enhanced graphics and interesting interpretations of what may have happened. They also use eye-catching headlines to attract viewers, but the science is disputable. 'Alien motorways' or 'Secret technologies of the ancients' arouse interest, and a quick, flashy style with some strong statements allude to their scientific accuracy, but they rarely stand up to scrutiny. Phrases like 'Scientists currently have no explanation for this' imply that scientists are actually researching the topic but do *not* state who or where this research is being undertaken, if at all.

Scepticism as a key skill

We would encourage a sceptical approach to everything but in particular science teaching. Sceptical enquiry is at the heart of what we do in science. Scientific scepticism does not set out to reject new ideas, but seeks to challenge what is claimed. In our terms, scepticism means that there should be compelling evidence presented openly before we are convinced. Scepticism lies at the core of science. Scientists gather data, hypothesise, test, then confirm or deny.

There is much bad science in the public domain. Great claims are made by public figures who wish to sell a product or a lifestyle. These claims should be challenged as part of our normal approach to everything, and the children we teach should be encouraged to do this. The abundance of social media platforms and the ease of establishing your own website have led to 'fake news' but also 'fake science'. This can make its way into schooling. For example, the 'Brain Gym' programme operated in many schools in a number of countries in the belief that by doing certain breathing and movement exercises we could improve our memory, cognition or intelligence. Children held their left nostril, rubbed their chest in a certain way, jumped up and down and generally exercised. In the main, they enjoyed it but it did not improve their brain capacity in any way whatsoever. Schools and education boards bought into this and paid a lot of money to the people teaching it. It had no evidence base and could not be shown to improve children's learning.

A sceptical or scientific approach is what we want to reinforce. There has been a resurgence in recent years of 'Flat Earth' believers. Using this as an example, how could we persuade young people that the Earth is round or spherical?

We could say:

1 When the Earth casts a shadow on the Moon, it is round.
2 When ships sail away from us, the last thing we see is the top of the ship as it goes over the horizon.
3 If we look carefully, we can see that the horizon curves.
4 Photographs from space may give extra evidence, although this could not be seen directly by the children.

Throughout all our lines of enquiry, we should encourage children to challenge and scrutinise what is being said to them.

Science and religion

Children's ideas about 'Life, the Universe and Everything' continually change. Their views are shaped and altered by everyday events. Television, the internet and overheard discussions all feed into their ideas of what things are and how they behave.

Teachers need to recognise that family, friends, the media and even they contribute to a child's awareness of the world around them. Children's reliance on sources during the early years can also be unquestioning, such as 'the teacher said so'. As written earlier, learning science involves developing a series of skills that involve observations, hypothesis testing and experimentation.

Faith and science are alternative philosophies. Science and religion may provide opposing ideas, notably where host communities' views oppose scientific ideas, in particular those relating to Darwin's theory of evolution (e.g. the creationist movement). The associated undermining of the science curriculum to provide a 'balanced' coverage between creationism and evolution is an example of curricular, not scientific, controversy.

Such conflict need not exist. It does not exist in science, nor does it exist in most religious thinking. Many past and current scientists have held and continue to hold strong religious beliefs. The Jesuit scholars within Roman Catholicism were responsible for great strides in astronomy, for example.

The *scientific evidence* to support evolutionary theory is overwhelming; belief in the existence of God is accepted by all major monotheistic faiths. Each describes different philosophical viewpoints. Whilst science changes our perceptions of the natural world, which is perhaps its prime purpose, it cannot be used to prove or disprove the existence of God through experimentation. In June 2019, Professor Brian Cox explained that he could not be sure there was no God, continuing that science cannot answer every question (Cox, 2019). The rhetoric of religious questions lies in different domains, and frequently invites questions that seek to explain our existence.

Scientific and pedagogical questions

An appropriately designed science education must not rely on memorising endless facts, but on the ability to ask, and attempt to answer, creative questions. Questioning is the heart of science. Findings to specific questions are the fuel that generates new ones. These questions may lead the enquirer in many different directions.

Teachers' questions

Teachers ask questions habitually to inform their professional insights. Epistemological questions impact on pedagogical knowledge, values progression and their audience. Pedagogical questions focus on teaching style, the learning environment, engagement and curricular matters. Bloom's taxonomy describes cognitive, affective and psychomotor questions. Social, cultural, political, ethical and evaluative questions add to the complexity of a teacher's professional analysis. While these questions are important and generate data, they are not necessarily scientific.

Scientific questions

Questions play a pivotal role in science. Scientific questions are objective – clearly defined, measurable and controllable. Unscientific questions are based on values or opinions. Good scientific questions can be answered by direct observations or with specific tools that are designed to capture events that are found beyond our senses. Compare, for example, the observations that might be made with binoculars during a field study into populations of migratory birds with the data that have been collected by the sensors that capture subatomic events within the Large Hadron Collider.

Children's questions

Children's questions are spontaneous and at times appear to be random in nature. Experienced teachers exploit such incidental learning opportunities; confident teachers and curricula build programmes of study around celebrating them. Systematic enquiry requires providing routines and structures that scaffold their investigation. A key skill in a teacher's repertoire is the ability to listen to the question the child is asking, or work out what they might mean to ask. Children's vocabulary may limit their articulation of a question but effective teachers can identify the underlying query.

Simple questions, however, often have incredibly difficult answers and giving an answer that is appropriate and at the correct stage is difficult.

'Why is the sky blue?' or 'Why does light pass through a window?' is very difficult to explain simply. The first four lines of Rudyard Kipling's poem 'I Keep Six Honest Serving-Men' can help provide a structure that will assist children to ask meaningful and well-structured questions:

> I keep six honest serving-men.
> They taught me all I knew.
> Their names are 'What' and 'Why' and 'When'
> And 'How' and 'Where' and 'Who'.

Effective teaching

National and local governments, potential employers, education authorities, parents and other stakeholders have considerable interest in ensuring that effective teaching takes place. The qualities of effective learning and teaching are complex and many education authorities provide standards by which they will attempt to assess the quality of the experience in schools.

We take 'effective' to indicate that it is carried out well.

We take 'learning' to refer to what children do during formal schooling, and elsewhere.

We take 'teaching' as the process of instruction carried out by professionals during formal schooling.

While experts might debate the features of a 'good' science education, the following behaviours, while not exhaustive, are offered as a starting point for effective science teaching.

What indicates effective teaching	How it may look in practice
Involves students in actively doing science	Ask thought-provoking, higher-order questions that encourage extended responses
Is inclusive, progressive and coherent	Course requirements are shared
Links science, technology, engineering and mathematics (STEM)	The interdisciplinary nature of real-life scenarios is used to explore the nature of modern progress
Builds on National Targets	Links between prior work are used to plan the next stage for children's progress
Helps students clarify, revise and build models of the world	Development of their level of understanding as more sophisticated models are used to explain the world around them
Determines appropriate learning outcomes	Using national framework(s) to plan appropriate schemes of work, taking into account the nature of the children in the school
Uses a balanced variety of methods	Enquiry, open-ended approaches, cooperative and collaborative approaches, teacher led, online. Teacher selects the approach best suited to the content and available resources
Ensures individual needs catered for by staff	Gathers intelligence about children's progress from all available sources. Children's voice is sought in the evaluation of topics
Provides suitable challenge	Using data gathered from children's prior work to inform teachers' planning for the next phase
Locates learning within appropriate contexts	Opportunities to use local resources and associated expertise to visit school or enhance experience

Teaching standards

Teaching standards set out to describe expectations at various stages of the profession. They can:

- provide a useful, albeit occasional checkpoint for experienced teachers;
- support professional development at the beginning of a career;
- be used by observers, e.g. school inspection, as the basis for critical analysis of practice.

Local standards will influence personal practice and best practice involves the establishment of personal plans that identify attainable professional development.

Numeracy

Numeracy is the ability to use numbers in ‘real life’, context-driven scenarios. It is not necessarily mathematical. It is the ability to use numerical data to communicate or make inferences regarding certain events.

The application of the numeracy skills included in mathematics and statistics is successfully deployed across the STEM subjects. Using number to describe what has happened in a particular event is one facet of scientific debate. Science and numeracy are inseparable. They provide opportunities to exercise logic, reasoning and critical thinking while reaching conclusions about observations, events and investigations. The impact of context-based learning cannot be overemphasised. The tasks that are built around data collection from first-hand direct experiences are exponentially more engaging than abstract ones that might characterise many number lessons. Measuring the length of a pole’s shadow at various times of day and then describing findings is an example of what we seek. Learning to apply numeracy skills within STEM can provide exciting and engaging tasks that lead to a ‘wow’ factor as well as gaining numerical and scientific insights.

Numeracy skills are progressive, involve communication, conform to conventions, can contribute to ICT, and assist in making sense of STEM’s empirical world. Numeracy skills also facilitate opportunities for raising confidence in the particular forms of graphics including signs, symbols, use of points, subscripts and superscripts, visual summaries, and formal use of language. Numerical vocabulary and language are essential to the development of observation skills (see, for example, ‘The famous 137-second plant hunt’ activity in Chapter 1).

Being confident with numbers provides learners with computational skills, life skills, such as calculating time, space and distance, estimating budgets and quantities, managing accounts, making sense of media reports on the economy and so on.

Numeracy extends well beyond ‘doing sums’. It includes solving problems, decision making and thinking in a logical manner. These are important in interpreting the barrage of data with which we are bombarded in this information age of the twenty-first century.

Working scientifically

Children’s exploration of the living and physical world is shaped by the experiences that they collect through observation and the ideas that they create for them. Activities in science provide countless opportunities for data collection using all the senses, e.g. chemical changes might involve colour and transparency changes (vision), effervescence (vision and hearing) and temperature changes (thermal receptors in skin). The impact of these data sets initiates the cognitive events that are involved in learning, which may involve the revision of previous ideas. Practical science can promote inclusion since individual activities need not rely on previous academic achievements, if all participants are encouraged to contribute their observations and resultant analysis.

Extensive literature has been written on working scientifically and what that entails in a primary classroom. We advocate an enquiry-based approach for many activities in this area. The skills of enquiry are not specific to science and they are easily transferable to other areas.

The basic principles of working scientifically are exemplified throughout the text and may include:

- discussing a phenomenon and trying to formulate a reason for it;
- suggesting a topic for enquiry;
- predicting or hypothesising what may occur;
- designing or constructing a method which will explore the topic;
- conducting the procedure;
- observing, measuring, recording or identifying an aspect of the procedure;
- reporting and evaluating.

These ‘skills’ can be further categorised into two main groups:

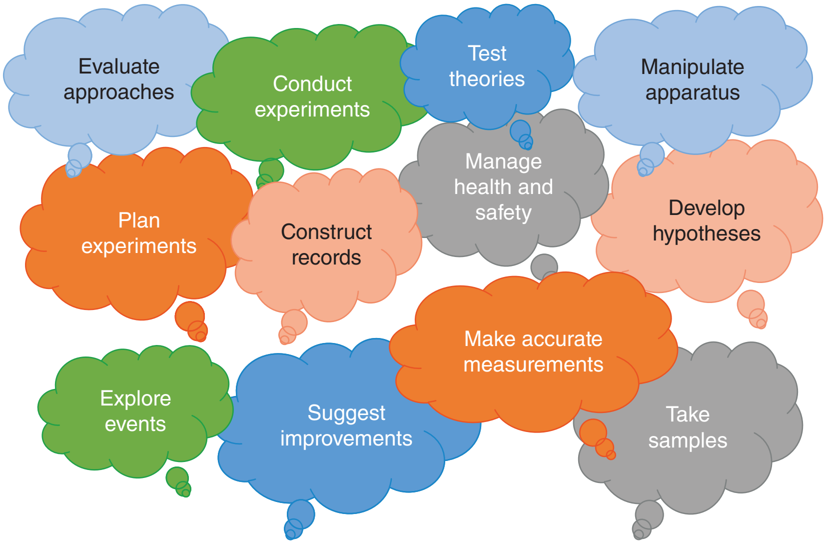
- Operational
- Reasoning/thinking

Scientific experiments

Experimental skills and strategies

While explaining primary science, we take the view that practical work is the driving force that lies behind children's progress in science. The word clouds below illustrate why it's important for children to engage in experiments and practical activities.

It is worth reminding ourselves that science is much more than a body of knowledge. The impact, scope and range of science on everyday life is inestimable. Smartphones, pharmacological advances and cosmological insights represent huge areas of scientific and technological research with associated economic benefits. It is unlikely that scientists in each of those areas would comprehend the nuances involved in the others; this represents a dilemma that confronts scientists, the general public and teachers, which is that everyone experiences shortcomings in their understanding of and confidence in the unknown. The dilemma becomes more problematic in an enquiry-driven classroom where we wish to promote engagement while avoiding providing 'the answer' and destroying the wonder.



What is an experiment?

A formal definition provided by the *Merriam-Webster Dictionary* (n.d.) is:

> an operation or procedure carried out under controlled conditions in order to discover an unknown effect or law, to test or establish a hypothesis or to illustrate a known law.

This definition may be difficult to reconcile within the primary context but any activity where you can illustrate or investigate an event should be taken as an experiment. You might carry out an experiment to *confirm* the change of state that takes place when a cake batter is heated in the oven. Alternatively, you might *investigate* the impact of baking when the batter's ingredients are changed. While procedures in each of these cases are identical, the learning outcomes are significantly different.

The manipulation and control of variables lies at the heart of investigative science. Scientists ask 'what might affect …?'; teachers and pupils might assimilate that question into the enquiry-led environment. The key for you as a teacher is to create the environment, to manage the learning so that the children generate these questions and with guidance formulate a method by which they can be examined.

Children's learning via enquiry-based science is comparable with the nature of science as it involves being introduced to and rehearsing a variety of problem-based strategies such as:

- Following procedures
- Explaining
- Focusing
- Hypothesising
- Identifying issues
- Analysing
- Collaborating
- Describing
- Wondering
- Evaluating and selecting options
- Experimenting
- Identifying variables
- Observing
- Predicting
- Quantifying
- Repeat testing
- Reporting
- Seeking solutions
- Enquiring
- Interpreting
- Justifying
- Listing
- Modelling
- Summarising
- Tabulating
- Using resources

Working with variables

There is considerable support available via professional bodies and national curriculum support organisations to teachers regarding the nature of experiences, which contributes to high-quality, scientifically robust and pedagogically sound scientific experiences.

Fair testing is a key characteristic that is introduced to young learners, initially in simple and well-supported examples; but as they develop, this scaffolding can be gradually withdrawn to allow for them to take control of their learning and to develop as scientists.

A fair test is one in which a number of variables are kept the same except for the item(s) under scrutiny. This leads to a categorisation of three variables which are found in every experiment.

- *The independent variable* – This is what can be changed (the temperature of the water, the height a ball is dropped from). The investigator's hypothesis will be that this variable may affect the outcome, the dependent variable.
- *The dependent variable* – This is what will be measured (the number of spoons of sugar dissolving, the height a ball rebounds to). The investigator believes this may be affected during the experiment.
- *The controlled variable(s)* – These are kept constant. During an investigation, or experiment, they must not be allowed to change, thereby ensuring they do not affect the outcomes.

It is clear, however, that science involves many different ways of working, amongst which are the routines involved in fair testing. One UK Primary Science Teacher of the Year, Beth Budden (2017), opined: 'science investigations in school are often focused on the traditional concept of a fair test. … Fair testing is only one approach to investigating science questions.'

Budden subscribed to four valid alternative approaches suggested at the time within the National Curriculum for Science for England:

1 *Observations over time* generate insights and data that promote speculation in relation to phenomena during the full range of time periods. Significant data accumulate and children and schools are encouraged to contribute to citizen science projects such as the Royal Society for Protection of Birds' (RSPB) annual birdwatch, contributing records to phenology projects or noting astronomical events.
2 *Pattern seeking* derived from observations, and these can refer to patterns of distribution or sequences in time.
3 *Identifying and classifying*, a characteristic human behaviour that helps to organise and make sense of the world – its most obvious application – but is not limited to aspects related to biodiversity. Filtering searches on the internet and the organisation of chemical elements into the periodic table are both examples that validate such approaches.
4 *Research* is a prerequisite. What do I know? What do others know? Where can I find out? What skills are needed? Clear overlap with literacy is evident and the IT

skills cannot be underestimated. Strategies towards safely selecting appropriate information are required.

Practical activities

Central to any science curriculum is the development of practical skills and their use in ‘real-life’ science. The benefit of practical work in science is not as straightforward as it may appear. Doing an experiment to highlight a point does not, by itself, lead to greater understanding. Pupils’ outcomes from undertaking an experiment can often be quite different from what a teacher desires.

Effective practical work or investigations allow students to establish a link between what they can see and do and the scientific explanations that lie beneath their activities. We advocate that teachers strive to make these links explicit (discussion, scene setting) and construct the task to focus on these links.

During practical activities, children’s knowledge can be enhanced by novel experiences or reinforce previous ones in order to develop theories. By understanding the scientific process, knowledge and research procedures, they can gain insight into ‘real-life’ applications. Skills development extends beyond those concerned with manipulation, resource and time management. Practical experiences encourage critical thinking skills such as analysis, questioning, reasoning and seeking patterns. Sharing findings verbally, in writing and graphically, provides rich, context-oriented communications, thereby extending literacy. Independent thinking and responsibility for managing the activities in a reliable and safe manner mirror ‘real’ science. Whether working independently or as part of a team, valuable life skills are provided and ultimately can contribute to citizens making informed decisions. Much of this is transferable.

Given both the validity and complexity of practical work, it is clear that it requires careful planning with carefully constructed learning objectives. If these are written effectively, they will provide both the pathway and the destination involved in the learning journey. Robin Millar (2009: 6) made the point that ‘the way a practical activity is designed and presented may have a significant influence on the extent to which its learning objective(s) is/are attained’.

Health and safety

There are few areas that raise greater anxiety while planning to teach science than those related to health and safety. Accidents that happen during science activities are extremely rare. While this reflects the attention to detail given by teachers to their own and pupils' safety by including health and safety considerations in the planning, this must not encourage complacency.

We encourage participatory learning with illustrative experiments, enquiry based on investigations and demonstrated activities, and it is vital that appropriate routines are conducted in ways that ensure personal safety for pupils and teachers alike.

The same advice holds true for many other activities undertaken by teachers in schools. Physical education, sporting events, outdoor activities, field trips, or visits to places of interest will have an associated risk. The management of the risk is often down to common sense and applying appropriate and simple approaches. Consider the activity, assess what possible risks there may be and manage the learning appropriately.

While we offer an extensive range of activities to support children's learning, please remember that these ideas and suggestions must follow the guidance provided by your local or national regulations. In England, Wales and Northern Ireland, support is provided by CLEAPSS (www.cleapss.org.uk) and in Scotland by SSERC (www.sserc.org.uk).

Don't panic! While it is recommended that risk assessments should be written for each practical activity you undertake with a class, these are invariably available online from your local/regional provider. Note also the outstanding support that can be provided in the UK by professional organisations such as the Association for Science Education (www.ase.org.uk), the Royal Society of Biology (www.rsb.org.uk), the Royal Society of Chemistry (www.rsc.org) and the Institute of Physics (www.iop.org).

Citizen science

The public, as non-scientists, have the skills, abilities and willingness to contribute to the collection of data that inform scientific research in a wide range of projects. In the UK, the RSPB's annual Big Garden Birdwatch involves more than half a million recorders. Other natural history projects include flying ant emergence, counting walruses from satellite images, spotting wildflowers and even collecting garden slugs. Further examples are found in recording astronomical and meteorological events. SETI, the search for extra-terrestrial intelligence, cleverly uses a screensaver on millions of personal computers to gather data. Volunteers in the UK record seasonal events, e.g. the first ladybird or swallow in spring, as 'Nature Detectives'. Atmospheric gas indicators and long-term physiological records provide further opportunities for citizens to contribute to the wealth of scientific data. In other words, citizens can provide meaningful data and contribute to science. Some training is usually involved and measures are built in to corroborate the quality and validity of volunteers' data. Encourage children to participate in local and national data gathering. This provides opportunities for them to engage with and contribute to real science.

Closely aligned to the ideas encapsulated within citizen science is the growth in everyday incidences of science that are current or in the headlines and the resultant public discourse.

Interdisciplinary learning

Interdisciplinary learning (IDL), sometimes referred to as cross-curricular learning, 'is a planned approach to learning which uses links across different subjects or disciplines to enhance learning' (Education Scotland, 2012: 2). The US National Science and Technology Council (2018), in justifying IDL, asserts that:

> The best STEM education provides an interdisciplinary approach to learning, where rigorous academic concepts are coupled with real-world applications and students use STEM in contexts that make connections between school, community, work, and the wider world. … Modern STEM education imparts not only skills such as critical thinking, problem solving, higher order thinking, design, and inference, but also behavioral competencies such as perseverance, adaptability, cooperation, organization, and responsibility. (p. 1)

If the STEM agenda is to be fulfilled, then it must be through STEM acting as the driver rather than the passenger. Although mathematics has traditionally been found at the heart of the primary curriculum, token attention has been given to science, engineering and technology – minority time and attention being typified in the 'science hour', 'craft fair' or 'nature table'. There have been a number of reports in Britain highlighting the weaknesses of a thematic approach in primary schools. The science in many 'thematic' approaches is marginalised, or trivialised, in comparison to the other aspects studied within the topic.

As with all good practice in learning and teaching, it is essential that experiences are built around explicit targets with clear outcomes. Distinctiveness is derived from exploiting the opportunities to draw learning outcomes from different curricular areas; pedagogical skill is required to ensure that the links are valid, that duplication is avoided, and learning is progressive on all fronts.

If we accept this vision of IDL as providing exemplary good practice, then we might also consider the impact on all learning contexts including in- and out-of-classroom learning.

We should consider when it is best to select independent or collaborative working, in taking responsibility or developing teamwork.

IT/ICT

We are living in the 'information age'. As with other periods in history, e.g. the transport age and the Industrial Revolution, the changes are embraced by enthusiasts and vilified by others.

According to TechTerms (n.d.), IT 'refers to anything related to computing technology, such as networking, hardware, software or the internet, or the people that work with these technologies', while ICT (Information and Communication Technology) 'refers to technologies that provide access to information through telecommunications'.

The internet supplies opportunities for real-time, global messaging, videoconferencing and social networking. Through the internet, today's learners have access to almost all knowledge, the nature of which is changing. Nevertheless, *understanding* does not necessarily proceed from the results of searching through a browser. Critical skills are required to discriminate between fact and fiction, real and fake news, etc., and these skills must be learned; programmes of study require planning to incorporate them.

Curriculum documents refer to the potential for IT/ICT to contribute to children's learning and support teaching. Although variation exists in local detail planning, IT/ICT should relate directly to learning outcomes in order to support effective teaching, enhance the quality of the learning environment and lead towards raising individual attainment.

IT/ICT should be regarded as providing opportunities to reach targets in science by analysing, demonstrating, interpreting, modelling, predicting and so on, i.e. enhancing science process skills.

Instrumentation, reliant on digital technology, is transforming our lives, e.g. apps that mediate aspects of life today such as domestic temperature and security via the internet, laser measurement, medical screening, etc. Although they have been developed for scientific, technological and commercial purposes, scientific suppliers have capitalised on the significant educational market. Similarly, scientific data can be collected, recorded and shared by using appropriate data loggers. These are electronic devices that collect information with sensors and record environmental parameters over time on a computer chip. Examples include optical instruments such as microscopes, telescopes and cameras, and data-logging devices designed to capture a full range of parameters including light, temperature, voltage and current, atmospheric gases, pulse, humidity and so on. Whatever data are recorded, they will be available in an electronic form, e.g. spreadsheet, or a JPEG that can be imported into pupil reports and presentations, thereby enhancing their appearance.

The use of handheld and other digital devices is widespread in schools but the underlying pedagogical approach in using these devices is not universally accepted. Frequently tablets are being used as little more than digital versions of ‘show me’ boards. Children are using devices to prepare reports, take images, etc. but the wider opportunities have yet to be fully realised. Their use, especially since the Covid-19 pandemic, has increased dramatically but perhaps not as effectively as they should be. While communication technology blossomed during that period, a wide range of videotelephony apps were deployed to maintain appropriately safe, secure and distanced contact between pupils and teachers. Practices were quickly established, and where possible, additional resources mobilised. Such ‘sticking plasters’ helped maintain formal schooling, with the online presence preserving contact between the teacher and the pupil. The exploitation of positive experiences, possibly due to the gravity of the situation, has not taken place. ‘Best practice’ was not captured, developed and shared to any great extent.

Classroom practice in ICT requires more than the hardware. Research, development, collaboration and CPD for teachers are essential to capitalise on those opportunities to enhance classroom practices and children’s learning in science and throughout their schooling.

Finally, this introduction suggests ‘doing’ science is complex and relates to matter, energy, space and time. The remaining chapters reflect curricular content to assist teachers’ planning.