Towards evidence-based practice in science education

Robin Millar with John Leach, Jonathan Osborne, Mary Ratcliffe, Vicky Hames, Andy Hind, Hannah Bartholomew, Sue Collins, Jenny Lewis, Phil Scott, Rick Duschl

This article argues that teaching should be informed by research and reports interim findings from three of the four projects from the Evidence-based Practice in Science Education (EPSE) Research Network.

Introduction: The idea of evidence-based education

Science teaching (like all teaching) involves making many decisions. Before teaching a topic, a teacher has to take decisions about the learning objectives and their relative priority, whether to follow a particular published scheme or devise their own order and sequence, what activities to include in each lesson, and so on. During every lesson, there is a constant stream of decisions about what to do next – let the current activity continue a bit longer, or make a change, what kinds of questions to ask, how long to allow pupils to answer, and so on. What informs all these decisions? What determines the actual choices made? Some are almost automatic, without much conscious reflection; others are deliberated over more overtly. To what extent are these influenced by knowledge that has arisen from science education research?

We could ask the same sorts of questions about other practitioners in science education: policymakers, examiners, writers of textbooks and teaching resources. Or about people who take decisions about resource allocation at school or LEA level, many of which influence the way science is resourced and taught. These people also do jobs that involve them in making choices and decisions. What informs these decisions, and how big a role does knowledge from research play?

The idea of ‘evidence-based education’ (or evidence-informed education) is that practice can be improved, leading to better outcomes for learners, if evidence from research is collected and applied systematically to inform the decisions that practitioners (of all sorts) have to take in the course of their work. Arguments for evidence-based education often draw parallels with medicine. Doctors also have to take many decisions. If we go to see a doctor, we expect him or her to have good reasons for the treatment recommended – some evidence that it is likely
to work. We might be uneasy if we thought it was just based on tradition – ‘what we’ve always done’. We like to feel that our treatment is based on the most recent research, and there is evidence that it is the best way to treat our condition. Is it possible for science education to become more evidence-informed in this sense?

Like all analogies, there are some aspects of this comparison that are thought-provoking and useful – and others where the parallels are not so clear. There are many examples of major initiatives being imposed on the education system without any systematic research to show that they are effective. Surely we ought to take a more ‘experimental’ approach to innovations – and indeed to some established practices – and test their effectiveness more rigorously before implementing them on the large scale. At the other end of the scale, there are the more local and small-scale decisions that individual teachers take about how they are going to teach X or Y to this year’s class. Often we make minor changes in the light of last year’s experience, or because of a new idea that we have thought of since then. Here it is probably not realistic (or even sensible) to expect such decisions to be based on knowledge arising from research – but they might still be informed by it, at either a general or a more specific level.

In other respects, however, education is quite different from medicine. In medicine, the intended outcome (e.g. a return to health, or survival for five years) is agreed by everyone involved and is easily measured. In education, there may not be complete agreement in detail about the intended outcomes of a particular piece of teaching – and it may be very difficult to measure them reliably or validly. It is also often the case in educational contexts that an innovation or change produces less dramatic or clear-cut change than might have been hoped for. For various reasons, the ‘system’ is not very sensitive to small changes. So it is harder than in many other fields to show that a change is having an effect – and, when we can, the size of the effect is often not very convincing to others whom we might want to influence. There are also the practical difficulties that in education we usually ‘treat’ classes rather than individuals, and that carefully controlled experiments to test if one way of doing something is better than another are very difficult to set up.

These and other challenges will have to be overcome if science education is to become more ‘evidence-based’. This is a long-term project, not a ‘quick fix’. For that reason, the full title of EPSE is ‘Towards evidence-based practice in science education’. The best we can hope to achieve in the three years for which the Network is funded is a better understanding of the factors which facilitate or hinder the impact of science education research on practice, and some evidence that the application of knowledge from research can, under certain circumstances, lead to improved learning.

Our main focus is on the teaching and learning of specific science ideas and ideas-about-science – and about how research on teaching and learning might inform this. The first two projects described below look at the teaching of specific science concepts and key ideas; the third looks at the teaching and learning of ‘ideas-about-science’ – the ideas and evidence strand of Sc1.

Robin Millar

The Evidence-based Practice in Science Education (EPSE) Research Network is part of the UK Economic and Social Research Council’s Teaching and Learning Research Programme (TLRP) – the largest programme of educational research ever conducted in the UK. EPSE is undertaking four related projects, whose overall aim is to help us understand better the relationship between science education research and practice, and thereby increase the impact of research, leading to improved learning of science by more pupils. The four EPSE projects are the only ones in the TLRP that focus specifically on science education.
EPSE Project 1: Using diagnostic assessment to improve science teaching and learning

Robin Millar and Vicky Hames

What the project is about

‘Evidence-based practice’ depends on being able to collect evidence about whatever we are interested in. In the case of science education, this would mean evidence of pupils’ learning in science. Collecting such evidence is not, however, a trivial matter, particularly if our aim is to develop ‘understanding’ or ‘skills’, rather than the ability simply to recall facts and terms. For example, it is easy to say that we want students at key stage 3 ‘to understand the particle model of solids, liquids and gases’ – but how would we know if a particular pupil had, or had not, achieved this? Making this ‘diagnosis’ requires that we have some questions or tasks which we can give to pupils, where differences in the way they respond will distinguish those who have ‘understood’ from those who haven’t. In many areas of science, it is not easy to operationalise the intended learning outcomes in this way – but it is very valuable to try to, as it both clarifies our objectives and opens them up to discussion.

Diagnostic questions or tasks are ones which give us as clear and precise information as possible about what an individual pupil understands – and perhaps also throw light on the source of any misunderstandings. Using diagnostic questions can help teachers to focus attention on the really important ideas that pupils have to grasp to make progress, and to monitor individual pupils’ progress in understanding. There is also considerable evidence from research that using assessment formatively, in the course of teaching, to monitor progress and provide feedback is a very powerful way of improving pupil performance (Black and Wiliam, 1998; Black et al., 2002).

Design of the study

In EPSE Project 1, we have worked with a group of teachers to develop banks of diagnostic questions in four science topic areas: electric circuits, force and motion, matter and chemical change, and biochemical life processes (digestion, respiration and photosynthesis). These topics were chosen in collaboration with the teacher group, as ones where diagnostic questions would be particularly valuable to support teaching and learning. A starting point was the questions used by researchers to probe pupils’ ideas. Our aim, however, is not to communicate the findings of such research to teachers, but rather to make more widely available some of the instruments and tools used by researchers, so that teachers can more easily collect diagnostic information in their own classes.

Questions have been improved and refined through critical discussion with the teacher group. We have also tested them with classes, interviewing a sample of pupils to check our interpretations of their written answers. For example, in the topic area of electric circuits, two-tier questions (of the kind suggested by Treagust, 1988) have proved to be very useful diagnostic tools. These are multiple-choice questions with two parts. The first asks pupils to select the correct prediction about a given situation; the second then asks them to choose one explanation from several provided. An example is shown in Figure 1. We find that most pupils’ answers to the two tiers are internally consistent, suggesting that they are not guessing – a common criticism of multiple-choice questions.

In Spring 2002, we used a selection of diagnostic questions from these banks to collect ‘benchmark’ data on pupils’ understanding of some key ideas at the end of key stages 2, 3 and 4. Perhaps surprisingly, given the amount of data collected nowadays on pupil performance, there is very little data available on how understanding of specific science ideas progresses as...
pupils move through the curriculum. In the current school year (2002–3), we are now exploring how these diagnostic questions might be used by teachers for formative assessment – monitoring pupils’ learning as teaching proceeds. We have given files of diagnostic questions to a group of teachers to use in their own teaching. Some suggestions about ways of using them are provided, but teachers are free to select and use the materials as they wish. We will be working with these teachers during the year to see how they make use of this resource bank. Two key questions are: does the provision of diagnostic questions enable teachers to make greater use of formative assessment, and does this lead to improvement in pupils’ learning?

Outcomes

This work is still in progress, so findings at this stage come from the diagnostic question development phase, and the ‘benchmark’ testing. One important finding concerns the reliability of testing procedures. Students’ responses to diagnostic questions testing the same basic idea are more variable than we might expect. For example, we included the questions in Figures 1 and 2 in the same test, taken by over 200 pupils at the end of year 9. For each question, we used their responses to deduce the ‘model’ of electric current they were using. The scientific model (current the same everywhere), for example, leads to answers 3/1 respectively for the two parts of Q1. An attenuation model, in which current is gradually ‘used up’ (or attenuated) as it goes round, leads to answers 1/2 or 2/2, depending on which direction the current is thought to go in. Some pupils may think the current is completely used up by the bulb – a consumption model – leading to answers 1/3 or 2/3.
Table 1  Models of current implicit in pupils’ answers to Q1 (Figure 1) and Q2 (Figure 2).
Note: CC = conventional current direction; EF = electron flow direction.

<table>
<thead>
<tr>
<th>Q1 scientific model</th>
<th>Q2 scientific model</th>
<th>attenuation (CC)</th>
<th>attenuation (EF)</th>
<th>consumption (CC)</th>
<th>consumption (EF)</th>
<th>other responses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>65</td>
<td>31</td>
<td>15</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>attenuation (CC)</td>
<td></td>
<td>4</td>
<td>38</td>
<td>11</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>attenuation (EF)</td>
<td></td>
<td>7</td>
<td>11</td>
<td>10</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>consumption (CC)</td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
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<tr>
<td>consumption (EF)</td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
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<tr>
<td>other responses</td>
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<td>6</td>
<td>3</td>
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<td>3</td>
<td>13</td>
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<tr>
<td>Total</td>
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<td>85</td>
<td>31</td>
<td>1</td>
<td>11</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>210</td>
</tr>
</tbody>
</table>

Table 1 shows the pattern of pupils’ answers to these two questions. In Q1, 197 pupils (94%) gave an answer consistent with one of these models; for Q2, the figure was 199 (95%). However, only 54% used the same model in both. Only 31% (65 pupils) used the scientific model for both, with almost as many basing their answers on an attenuation model. Of the 115 pupils who answered Q1 in line with the scientific model, only 65 used this model when answering Q2. Conversely, of the 82 pupils who answered Q2 in line with the scientific model, only 65 used this model when answering Q1. It would, therefore, be risky to conclude that a pupil ‘understood’ the scientific model on the basis of a correct answer to any one question.

Another way to explore consistency of pupil responses is to look at answers to all the questions in the ‘benchmark’ test which probed understanding of electric current. In the key stage 3 test, there were five. Table 2 shows the number of pupils who gave answers consistent with the scientific model (current the same everywhere) to all five, and to 4, 3, 2, 1 and none. If we take 4 or more correct out of 5 as our criterion for ‘understanding’, then 24% of this sample achieve this. If we lower the criterion to 3 or more correct out of 5, the figure rises to 43%. Again it is clear that a correct answer to one question in isolation is a poor measure of understanding.

The ‘benchmark’ tests for key stages 2 and 3 contained some common questions, as did those for key stages 3 and 4. Data from these questions provided information on pupils’ progress in understanding. In general, answers showed progress in understanding with age. In electric circuits, however, a ‘plateau’ appeared to be reached at quite an early stage. For some fundamental concepts, levels of understanding were low. For example, fewer than 10% of the key stage 3 and 4 samples appeared to understand that adding another resistor in parallel makes the total resistance less, or that an object which is slowing down (such as a ball that has been kicked) is not experiencing a force in its direction of motion. Over 40% at key stage 4 were unable to distinguish reliably between particle model ‘pictures’ of mixtures and compounds.

Table 2  Consistency of pupils’ responses to five questions probing understanding of electric current.

<table>
<thead>
<tr>
<th>Number of questions correct</th>
<th>Number of pupils</th>
<th>Per cent</th>
<th>Cumulative per cent</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>29</td>
<td>13.7</td>
<td>13.7</td>
</tr>
<tr>
<td>4</td>
<td>21</td>
<td>10.0</td>
<td>23.7</td>
</tr>
<tr>
<td>3</td>
<td>41</td>
<td>19.4</td>
<td>43.1</td>
</tr>
<tr>
<td>2</td>
<td>47</td>
<td>22.3</td>
<td>65.4</td>
</tr>
<tr>
<td>1</td>
<td>34</td>
<td>16.1</td>
<td>81.5</td>
</tr>
<tr>
<td>0</td>
<td>39</td>
<td>18.5</td>
<td>100.0</td>
</tr>
<tr>
<td>Total</td>
<td>211</td>
<td>100.0</td>
<td></td>
</tr>
</tbody>
</table>
Teachers involved in developing and pilot testing these diagnostic questions have reported on various ways in which this has helped them improve their teaching (see Box 1). The final phase of the project, on using these diagnostic questions for formative assessment, will explore these effects on teaching more fully. We hope to be able to report on this in SSR in due course.

**Box 1 Comments of some teachers involved in EPSE Project 1**

**Simon Carson, Norton College**

Students’ answers have started several fruitful discussions and have shown that even the brightest students can have difficulties with basic ideas. When students have committed themselves to a particular point of view on paper, they seem more ready to defend that point of view in public. This has drawbacks as well as advantages; some students feel that they have a stake in their (wrong) ideas and are all the more determined not to change them. But without the questions, I might never have been aware of how widespread particular misconceptions were! Either way, open discussion of misconceptions on a whole-class basis allows them to be tackled and enables me as a teacher to do more than give students the correct ‘examination answer veneer’ that does nothing to change their underlying world view.

**Brian Cowie, Barby High School**

What was surprising (and rather worrying) was the way the questions highlighted misconceptions held by our pupils. Most key stage 3 and 4 pupils chose a representation of particles in a liquid that showed them far more spread out than in a solid – even though we had been sure most had this model ‘on-board’. Even higher tier GCSE candidates got simple questions on resistance and voltage in circuits wrong. The diagnostic tests were a timely reminder that we needed to revisit a number of key ideas. The material also led to some interesting discussions within the department. Teachers are now using some of the probe ideas within lessons. The EPSE materials are a quick and manageable way to check pupil understanding, and also useful for teaching conceptually difficult areas in the science curriculum.

**Alyson Middlemass, The Elizabethan High School, Retford**

Using some written diagnostic questions on conservation of mass, I found that a lot of year 7 pupils were very unsure about whether the reading on a balance would increase, decrease or stay the same when sugar is dissolved in water, or even when a stone or a wood block is put into a beaker of water. My colleagues thought year 9 would have no difficulties with this, but I wasn’t so sure. When I tried it, there was a lot of discussion and debate, which we resolved by trying it out practically and seeing what really happened. It was a really good lesson – they were all very keen to see what the results would be and did the practical work carefully because they knew what they were trying to find out.
EPSE Project 2: Designing and evaluating short teaching sequences, informed by research evidence

John Leach, Andy Hind, Jenny Lewis and Phil Scott

What is the project about?

Although a lot of research has been conducted on young people’s learning of science concepts, it is difficult to argue that this research has had a significant impact on improving the scientific understanding of most pupils in UK schools. Some small-scale studies do exist which show that it is possible to improve pupils’ performance by changing teaching approaches, based on findings from research. However, the teachers in these studies tend to be working very hard to develop one aspect of their teaching, usually as part of a Masters or Doctoral degree. It is certainly not possible to conclude that other teachers, not involved in the design of the teaching, would achieve similar improvements if they attempted to implement the same teaching approaches with their classes.

EPSE Project 2 has two overall aims. The first is to investigate further the process of designing, implementing and evaluating short teaching sequences which draw upon insights from research on teaching and learning science. The second is to learn more about the factors which influence successful uptake of innovations by teachers not involved in their design.

The design of the study

A group of teachers and researchers worked collaboratively on the design of three short teaching sequences, on electric circuits at key stage 3, the particulate nature of matter at key stage 3, and plant nutrition at key stages 3 and 4. The main factors influencing the design of these teaching sequences were:

■ The professional knowledge and expertise of the participating teachers and researchers.
■ The content specified in the National Curriculum.

■ Insights from the research literature about particular conceptual difficulties experienced by pupils in relevant areas of the curriculum (‘learning demands’, see Leach and Scott, 1995)
■ Insights about the significance of teacher–pupil communication in science learning (‘social constructivism’; see Hodson and Hodson, 1998)

The teachers then taught the sequences to their pupils. In each case, a similar class was taught by another teacher, following the school’s usual approach. We are not claiming that this is a controlled experiment for obvious reasons: nominally similar groups can be very different. Nonetheless, such baseline information allows us to hypothesise about the likelihood that the designed teaching sequences are supporting pupils’ learning in specific ways.

We collected four different types of data:

■ Information about pupils’ understanding, from diagnostic questions administered before teaching, after teaching, and several weeks after teaching.
■ Information, from interviews with teachers at various stages and recordings of planning meetings, about how they felt about using the teaching sequences, including whether they saw these as compatible with their usual teaching style.
■ Information about how the teachers actually implemented the teaching sequences in their classrooms, with a particular focus on the way ideas were introduced, and teachers’ interactions with pupils. This involved video-recording all lessons.
■ Information about the teachers’ usual teaching styles, obtained by video-recording other lessons where the teacher is teaching conceptually demanding content to pupils of a similar age and ability.
A second stage of the project then involves finding out what happens when the teaching sequences are used by teachers not involved in their design. We are currently in the process of passing the physics and biology teaching sequences to other teachers not involved in their development, and investigating how they are implemented. (The chemistry sequence had some limitations, and we did not attempt to pass it to other teachers.)

We hope to complete 13 full case studies of the implementation of the teaching sequences by the end of the project, with a further 22 case studies where we collect data on pupil learning without teacher interviews or video records. This set of case studies will be used to provide insights into:

- **The impact of the designed teaching sequences on student learning.** The sequences were designed to address explicit learning goals. In order to evaluate the success of the sequences at meeting these goals, we tested pupils’ understanding of key conceptual content before teaching, after teaching, and several months after teaching, using diagnostic questions similar to those designed in Project 1.

- **The ways in which the teachers use the designed sequences.** The sequences were designed to address specific content in a particular order, to provide teachers with opportunities to *present* scientific ideas to pupils, and to *discuss* with pupils their developing understanding. We were interested in how the teachers used the planned sequences, and how and why they made the modifications that they did. In order to compare whether the teaching did indeed follow the planned sequence, we made a video recording of all the lessons in each sequence, using a single static camera with a wide-angle lens. In addition, the teacher wore a tie-microphone so we could hear all conversations between the teacher and pupils. We analysed these data in two different ways. The first focused upon the *thematic content* of the lessons. We examined the video evidence to look at the sequencing and conceptual content of the lessons, to identify similarities and differences of emphasis between the lessons as taught and the lessons as planned. The second focused upon the *communicative approach.* We examined the teacher–pupil talk to see whether it focused upon conceptual content, classroom management, or demonstration of techniques. For talk that focused on conceptual content, we were interested in the ways in which teachers worked with pupils to move towards an understanding of the scientific content. The teacher–pupil talk was analysed along two dimensions, interactive/non-interactive and authoritative/dialogic. Interactive talk involves questions and answers, whereas non-interactive means the teacher simply presenting ideas. Authoritative talk focuses on the scientific point of view, whilst dialogic talk takes account of different points of view (possibly including both the pupils’ views and the scientific point of view). It is important to emphasise that we do not see authoritative and dialogic talk as inherently good or bad. Rather, we were interested in the ways in which each kind of talk was used by the teacher in addressing the learning goals planned in the teaching sequence.

- **Similarities and differences between individual teachers’ teaching styles when implementing the designed lessons, and their usual teaching styles.** We compared communicative-approach analyses of the designed lessons with another lesson taught by the same teacher, which was not part of the designed sequence but also addressed conceptually demanding content. Although such comparisons can never be exact, we used this evidence (along with teachers’ comments in interviews) to hypothesise about the extent to which the teachers adopted different styles during the designed lessons.

By the end of the project we will be in a position to say something about the factors which support the teachers in successfully implementing teaching approaches informed by research evidence, and those which create barriers to successful implementation.

**A flavour of the teaching**

Were the lessons that we developed different from good science lessons taught in schools every day of the school year – and if so, how? In some respects, the lessons are reassuringly familiar. For example, the *thematic content* aim of the electricity unit is to develop pupils’ understanding of a charge-carrying-energy model of simple electric circuits. Lessons include activities where pupils think about an analogy for a circuit, measure current, predict the relative brightness of bulbs, and so on.
There are, however, some subtle but important differences. All three units start with pupils completing diagnostic questions (similar to those described for Project 1), to provide their teachers (and themselves) with insights about their prior understanding. The electricity unit moves on to an activity called The BIG Circuit. This consists of a bulb at one end of the lab, a battery at the other, and very long wires running around the room to make a simple series circuit. Many pupils predict that it will take a measurable amount of time between connecting the battery and the bulb lighting, indicating a model of electric circuits that involves ‘something’ starting in the battery and moving to the bulb. (Contrast this with the observation that energy is transferred as soon as current starts to flow.) The BIG Circuit activity was designed with insight into pupils’ likely thinking about electric circuits, as a memorable activity to allow the teacher to open up questions about electricity, current, energy and charge with pupils.

The lessons then continue with the systematic development of an analogy to explain how energy is carried from the battery to the bulb and then transferred through heating and lighting, at the flick of a switch. The analogy is with a fleet of bread vans delivering bread to a supermarket, and is of a type which will be familiar to many readers. This analogy is developed in a more extended and systematic way than is usual, and was used as a point of reference in all subsequent lessons. Thus, the pupils were encouraged to move, in their thinking and talking, between the supermarket analogy, their developing model of the electric circuit (involving charges carrying energy) and their practical observations and measurements. Particular features of the analogy were used to address specific content aims that research suggests pupils find difficult. To this extent, research insights about teaching and learning about electricity informed the way in which we developed both the aims and activities of the lessons.

The teaching sequence also differs from those typically used in schools in that specific guidance is given about the communicative approach. This highlights the different types of talk (presenting, discussing/probing, and supporting) and writing (recording and reviewing/applying) that might be used in the lessons, with brief notes on the purposes of each type. A set of icons is introduced which are then used throughout the lesson notes to indicate the type of communication intended for each lesson phase.

**Findings**

As the work is still in progress, conclusions are necessarily tentative. Some patterns, however, are beginning to emerge. In all except one of the case studies analysed so far, pupils following the designed teaching sequences performed significantly better on diagnostic questions probing conceptual understanding than their peers in the same school. This may be partly explained by the fact that the designed sequence emphasised understanding of the concepts tested. These were, however, ‘mainstream’ ideas, specifically mentioned in the science National Curriculum which would be expected to be covered in any teaching scheme. In contrast, there was no difference in performance on questions requiring factual recall (such as predicting what will happen to the brightness of the bulbs if a second one is added to a simple series circuit).

Teachers’ reactions to the designed teaching sequences varied considerably. A key influence appears to be how closely the teacher’s preferred style of teaching matches that advocated in the teaching sequence. Unsurprisingly, it seems that teachers who tend to use dialogic talk in their usual teaching use significantly more dialogic talk in the designed teaching. In several case studies, teachers spent more time in the designed teaching sequences than in comparable ‘normal’ teaching on conceptually focused interactions with pupils, and more of these interactions involved teachers listening, and responding meaningfully, to pupils’ ideas, interests and difficulties through dialogic talk. We are not yet in a position to draw firm conclusions about the relationship between pupil learning and the communicative approach adopted by the teacher. There is, however, some early evidence that a coherent presentation of thematic content, through authoritative talk alone, is not particularly successful in promoting pupil learning.

The last set of findings relates to teachers’ reactions to participation in the project. We were concerned that good science teachers should not feel constrained by the teaching sequences. They should not feel that they were being asked to follow a ‘script’ that robbed them of their professional autonomy and undermined their creativity in responding to classroom situations. Our analysis of data to date reassures us that teachers did not feel unduly constrained or
‘scripted’ during the lessons. Rather, they appeared to find their participation in the project a professionally fulfilling experience, as the comments in Box 2 indicate.

**Box 2**

**Comments of some teachers involved in EPSE Project 2**

**Andy talking about how his thinking about teaching the particulate nature of matter changed as a result of participating in the project:**

What we ended up doing was thoroughly understanding and explaining the particle model of matter, including things that I would never normally teach, like spacings of particles. What we’re doing is making use of the modelling in a complex situation, which I think is a high-level skill. In the discussion, the kids were constantly having to think about the modelling, the difference between an observation and an explanation. One of the most beneficial things I take forward is that these kids do not understand the particle theory of matter after our usual teaching.

**Sarah talking about how her appreciation of her pupils’ thinking had changed as a result of participating in the project:**

When I first started teaching here, I was still doing all these misconception things. I used to ask them stuff and I used to always be disappointed that they’d give me the right answer. I don’t still think that, I know that there was a much bigger level of misconceptions with year 9 than there was with year 7. There were some very intelligent kids there who had got the wrong idea, so misconceptions are definitely there with all of the kids. I think a lot of kids get a lot of GCSEs and they don’t understand a lot of what they’ve done. I mean, we can teach them to jump through hoops and we’ve got the sort of kids who will very happily jump through whichever hoop you give them, but it doesn’t mean they understand it and we often find A-level kids with really good grades have some very strange ideas. I think with exam results all the time, the emphasis is on achievement, not on learning particularly.

**Ashley talking about his general feelings about how the teaching went:**

I think I got some good responses. You know, those little teacher things we were talking about, those little dialogues you have with the kids, I think that was coming through. By the end I just seemed to be on a roll in that last lesson. It just seemed to go really well. They had understood everything that we did. It was very enjoyable actually – a lot more so than it might have been just doing it the standard battery and bulb method.
EPSE Project 3: Teaching pupils ‘ideas-about-science’

Jonathan Osborne, Mary Ratcliffe, Hannah Bartholomew, Sue Collins, Rick Duschl

What is the project about?

The introduction of ‘science for all’ has placed new pressures on science curricula and raised questions about what kind of science is really appropriate for the majority of pupils, most of whom will cease any formal education in science at age 16. The report Beyond 2000: Science education for the future (Millar and Osborne, 1998) was one stimulus to the debate here in the UK; similar debates have been taking place in many countries across the globe. One general point emerging is that we can no longer continue to offer a science education which is solely the first rung on the ladder to becoming a scientist. Rather, given that scientific issues increasingly dominate the news and pose many of the political, ethical and moral dilemmas of the day, it is important also to teach young people some ‘ideas-about-science’. This argument has been supported by reports from the House of Lords (2000) and the House of Commons Science and Technology Committee (2002). Evidence submitted to the House of Commons Committee by pupils, and the findings of a study by Osborne and Collins (2000), show that many pupils find the lack of space in existing curricula to raise and explore contemporary science issues to be frustrating and alienating. In effect the gulf between science-as-it-is-perceived and science-as-it-is-taught has become too large and there is a need to bring the two much more closely together.

These demands, however, pose a number of significant problems for teachers of science. First, what should be taught? And, second, how can it be taught successfully? These are the questions which EPSE Project 3 addressed. Its aim was to provide answers that are based on evidence, and not just opinion. Until now, answers to the first question have suggested that pupils need to be taught much more about the nature and limitations of scientific evidence, how scientists work to produce reliable knowledge, ideas of risk and more. Yet there is little ‘expert’ consensus about the nature of science and what scientists do. Indeed the high-profile debate in the academic community between sociologists, philosophers and scientists about the nature of science has often been so acrimonious that it was dubbed ‘the science wars’. If people who are engaged in the practice of science and in the study of its practice cannot agree, what can be expected of those who teach science?

Even if agreement can be reached about what to teach, there is another fundamental problem confronting science teachers. Only a few of us have had any formal education about the nature of science. Consequently, many of us have little idea of how to teach about the nature of science and there is only a rather disparate collection of materials available to assist.

Phase 1

In the first phase of EPSE Project 3 we attempted to address the first question (what should be taught?) by conducting a survey of the views of 23 publicly acknowledged experts including scientists, philosophers and sociologists of science, people involved in communicating science to the public, science teachers and science educators. Using three rounds of linked questionnaires, where the responses were sifted and successively commented on, we sought to identify the level of agreement amongst these experts about which ‘ideas-about-science’ were so important that they should be included in school science. We found a strong consensus about nine common themes, or elements of ‘ideas-about-science’, that should be part of the 5–16 science curriculum (Osborne et al., 2001). These are summarised in Figure 3.

Whilst this is by no means a comprehensive account of science and its nature, these components form the core of a ‘vulgarised’ account of science and its nature – a version which would give school science pupils some of the intellectual tools necessary to make...
### Theme title and summary

**NATURE OF SCIENTIFIC KNOWLEDGE**

**Science and certainty**
Students should appreciate why much scientific knowledge, particularly that taught in school science, is well-established and beyond reasonable doubt, and why other scientific knowledge is more open to legitimate doubt. It should be explained that current scientific knowledge is the best we have but may be subject to change in the future, given new evidence or new interpretations of old evidence.

**Historical development of scientific knowledge**
Students should be taught some of the historical background to the development of scientific knowledge.

**METHODS OF SCIENCE**

**Scientific methods and critical testing**
Students should be taught that science uses the experimental method to test ideas, and, in particular, about certain basic techniques such as the use of controls. It should be made clear that the outcome of a single experiment is rarely sufficient to establish a knowledge claim.

**Analysis and interpretation of data**
Students should be taught that the practice of science involves skilful analysis and interpretation of data. Scientific knowledge claims do not emerge simply from the data but through a process of interpretation and theory building that can require sophisticated skills. It is possible for scientists legitimately to come to different interpretations of the same data and, therefore, to disagree.

**Hypothesis and prediction**
Students should be taught that scientists develop hypotheses and predictions about natural phenomena. This process is essential to the development of new knowledge claims.

**Diversity of scientific thinking**
Students should be taught that science uses a range of methods and approaches and that there is no one scientific method or approach.

**Creativity**
Students should appreciate that science is an activity that involves creativity and imagination as much as many other human activities, and that some scientific ideas are enormous intellectual achievements. Scientists, as much as any other profession, are passionate and involved humans whose work relies on inspiration and imagination.

**Science and questioning**
Students should be taught that an important aspect of the work of a scientist is the continual and cyclical process of asking questions and seeking answers, which then lead to new questions. This process leads to the emergence of new scientific theories and techniques which are then tested empirically.

**INSTITUTIONS AND SOCIAL PRACTICES IN SCIENCE**

**Cooperation and collaboration in development of scientific knowledge**
Students should be taught that scientific work is a communal and competitive activity. Whilst individuals may make significant contributions, scientific work is often carried out in groups, frequently of a multidisciplinary and international nature. New knowledge claims are generally shared and, to be accepted by the community, must survive a process of critical peer review.

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**Figure 3** Major themes that should be included in the school science curriculum, emerging from the Delphi Study.

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sense of contemporary science and would form the foundation on which a more sophisticated understanding could later be built.

**Phase 2**
In the second phase of the project, we worked with eleven teachers of science at key stages 2, 3 and 4 to develop a range of strategies and materials for teaching these nine themes. We then studied how the teachers used these materials, noting their successes and also any difficulties that they experienced. The materials were drawn from a large range of sources, with some written by the teachers themselves. One is shown in Figure 4.
**Themes addressed:** Science and certainty  
Hypothesis and prediction

**Aim:** The aim of this lesson is to:
- explore the relationship between ideas and evidence;
- show how the interpretation of evidence depends on developing a hypothesis or theory that is consistent with the evidence; and  
- to show that new evidence requires old theories to be re-evaluated.

**Resources:** OHTs 1, 2 and 3

<table>
<thead>
<tr>
<th>Timing</th>
<th>Action</th>
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| 5 min  | Begin by explaining the aim of the lesson.  
Emphasise that the lesson is not about a ‘right answer’ but engaging in the process of doing science and interpreting evidence.  
Put pupils in groups of four. Ask them to imagine that they have been excavating fossils at a site in Europe when they uncover the following (show OHT 1).  
Ask them to develop a theory about what they think they have found. |
| 5 min  | Ask each group to present their theories.  
Note that they will be different.  
Discuss if it is possible to decide between them. |
| 5 min  | Now present OHT 2 telling them that they do a bit more digging and this is what they now find.  
In the light of this evidence, do they want to revise their theory? |
| 10 min | Ask each group to report back and explain if they have changed their theory and if so why.  
Discuss any issues arising. |
| 5 min  | Tell them that they do some more digging and this is what they find. Present OHT 3 and ask each group to consider whether they want to revise their theories again. |
| 5 min  | Now ask them to consider which of the following more accurately describes the nature of evidence and theories in science:  
(a) Scientists do experiments and look for patterns from which they obtain explanations or laws.  
(b) Scientists make observations, develop ideas (hypotheses) and then test these against the data that they collect. |

**Figure 4** Outline plan for a lesson to teach about the relationship between theory and evidence in science.

Our findings suggest that teaching ‘ideas-about-science’ poses a number of significant challenges for many science teachers. Our analysis of video-recordings of teachers’ practice suggests that these challenges can be characterised by the five dimensions shown in Figure 5. Teaching the nature of science successfully, we found, required an ability to operate on the right-hand side of some or all of these dimensions. Teachers who were able to do this tended to be more effective in getting across the key ideas.
Figure 5 Five dimensions of effective practice when teaching the nature of science (NOS).

Several also reported that the work enabled them to gain new insights into pupils’ thinking, as the comments in Box 3 indicate.

Box 3 Comments of some teachers involved in EPSE Project 3

<table>
<thead>
<tr>
<th>Judy Machin, Gumley House School</th>
<th>Natasha Wilson, Torriano Junior School</th>
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<td>I see the major benefit of it [teaching about science] as setting science into its historical perspective. Because when you have grown up with a subject and you have done it in depth you appreciate the development of ideas, but I think we have failed to realise that the kids need to appreciate the development of ideas as well, and not just be splatted with something that is what we know now.... I think that all the work we've been doing is to do with developing a coherency about the subject.</td>
<td>I think the most enjoyable bit [of trying these materials and approaches] was the surprises, responses from the children. It has just given me a completely different perspective on some children and their views about science and how they see science, particularly my children with special needs and with literacy problems. I think the way that the activities that I did for the project, gave them a chance to actually really express their ideas on science. And in fact, I found they were very capable scientists. They were good science thinkers, and I’d never actually really thought about that before.</td>
</tr>
</tbody>
</table>

Further information on the EPSE projects

Readers interested in finding out more about the EPSE Research Network will find more information about the projects described above on the EPSE website: www.york.ac.uk/depts/educ/projs/EPSE. The teaching materials outlined in the article, and others developed by the Network, can be downloaded from the website.

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Towards evidence-based practice

References


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