The practical work challenge: incorporating the explicit teaching of evidence in subject content

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ABSTRACT The new National Curriculum in England aims for pupils to understand traditional ideas in biology, chemistry and physics as well as to understand evidence, as specified in '*Working scientifically*'. It also instructs that '*Working scientifically... must always be taught through and clearly related to substantive science content*'. This rubric could present a challenge to meeting the aims of the curriculum and teachers will have to plan their teaching, including the use of practical work, carefully to overcome this challenge.

In England, the Department for Education (2014) has recently created a new National Curriculum for science, the aims of which include that all pupils should:

develop understanding of the nature, processes and methods of science through different types of science enquiries that help them to answer scientific questions about the world around them

While the explicit inclusion of different types of science enquiries as a means of exploring the real world is very welcome, we have to consider carefully what it is that pupils need to be taught so that they develop an *understanding* of the nature, processes and methods of science. After all, we do not want the routinised approach to the recently pervasive 'lab-based fair testing'-type investigations (Roberts, 2004) just to be replaced by an extended repertoire of different 'recipes' for other approaches! So what is there to understand?

At the core, science is fundamentally about establishing lines of evidence and using the evidence to develop and refine explanations using theories, models, hypotheses, measurements, and observations. (National Research Council, 2007: 18)

Understanding evidence means understanding about the reliability and validity of data, whatever approach is used to collect such data. We will address this first and then consider the role of practical work in meeting these curriculum aims.

Under-specification of the new curriculum

Despite the new curriculum's aim of pupils understanding evidence, it is not clear about specifically what it is that pupils should learn. This is not a new problem! But we should not be just repeating the mistakes of the past. Rather, we need to learn from well-established, but often ignored, research and resources that to understand the nature, processes and methods of science includes developing an understanding of evidence.

Yet again, the specification in the new curriculum documents is expressed in terms that describe what they expect pupils '*should be taught so that they develop understanding and first-hand experience of:... planning experiments... carrying out experiments... making and recording observations... evaluating methods... to evaluate data...*', etc. (Department for Education, 2014). Listing such activities compiles a *description* of '*Working scientifically*'. Going beyond just superficial imitations of others' actions requires that we teach pupils the ideas needed to make the decisions necessary when collecting evidence and making a claim; the ideas that underpin all this '*Working scientifically*'. In other words, we need to teach the 'thinking behind the doing'. Once again, the 'thinking behind the doing' has not been specified in the curriculum despite it being these ideas that are necessary to *understand* evidence in '*Working scientifically*' and that are vital for curriculum planning.

What is meant by understanding evidence and how might practical work help develop pupils' understanding of evidence?

Understanding evidence

The difference between a descriptive account of working scientifically and a focus on the ideas required to make decisions can be illustrated with reference to a few examples.

For instance, the key issue in an investigation is not so much the process of gathering readings but the decision about how much data to collect. Here, the amount of data needed depends on the particular circumstances – there is no set figure. Essentially, the thinking behind deciding on a number of readings involves an assessment of the variation in the readings in relation to the effect on the dependent variable of any change in the independent variable. This thinking uses ideas or concepts.

Similarly, choosing an instrument should involve an evaluation of its appropriateness in relation to the task at hand. This involves thinking about:

- whether an instrument is, for instance, sensitive enough for the values being measured – a key consideration in a local dispute about potentially harmful pollutants being emitted from a chimney (Roberts and Gott, 2010);
- whether it is specific only to what it purportedly measures – with the concomitant dangers associated with false positives;
- an instrument's effect on the resultant data in relation to the question asked; for instance, any unrecognised imprecision of a set of scales may not have significant consequences if it only affects the amount someone might next eat at breakfast but the poor precision could have a dire impact if change in mass were being used as an indicator of, say, a serious medical condition.

Pupils' ability to '*apply sampling techniques*', as specified in the new National Curriculum, in anything other than a routine way can only be demonstrated if pupils have an understanding of variation within the variables of an investigation and they make decisions about the sample collected in relation to the question being investigated. Thus in 'quality-controlled' things, such as sucrose, there is no variation within a kind (a substance is a substance) but the purity of samples is important and needs to be considered. With variables that exhibit variation in their distribution (such as plants growing in a habitat, red blood cells on a haemocytometer slide or the flowrate in a stream) or that change over time (such as air temperature, wind speed or the number of birds at a feeding station), the technique employed (random or systematic) and the size of the sample of data collected will need to be evaluated and this thinking uses ideas or concepts about the quality of evidence, as recognised by Millar *et al*, (1994) and detailed in Gott and Duggan (2003).

A major outcome of research reported in Hunt (2010) for SCORE (Science Community Representing Education – a partnership between the Association for Science Education, the Institute of Physics, the Royal Society, the Royal Society of Chemistry and the Society of Biology) was the specification of the ideas required for the 'thinking behind the doing' relevant at key stage 4 (ages 14–16) (see Box 1). Thus, we have a clear specification of 'what' to teach pupils so that they can understand the descriptions provided in '*Working scientifically*'. As Hunt (2010: 4) stated, '*The ideas* [in Box 1] *can be regarded as a starting point for discussion about their place in the curriculum. Once there is agreement about which ideas should be taught… then there can be a debate on how best to teach them*'. It is to this that we now turn.

Teaching about evidence and practical work

A very simple typology (Figure 1) shows that both practical and non-practical work can be employed as ways to teach the substantive ideas of biology, chemistry and physics and also to help pupils develop an understanding of evidence. Practical work – here referring to any science teaching and learning activity in which pupils manipulate or observe real-life objects or materials – is used extensively in secondary school science, mainly inside the lab but also with many possibilities for learning outside the classroom.

As Millar (2009: 5) points out, practical activities used to develop pupils' understanding are unlikely to work on their own; non-practical teaching must also be built in to the practical session to help the pupils' developing understanding:

Practical activities that strongly involve the domain of ideas have a significantly higher

		HOW TO TEACH	
		Practical activities which might include:	Other **'non-practical' activities** which might include:
WHAT O TEACH	**Substantive ideas**	• observation of objects or events and their classification • illustrative practicals • 'discovery' learning and enquiry practicals	• discussion • didactic teaching • active learning using text • presentations • the use of models
	Ideas about evidence	• whole and parts of investigations in the field and lab • illustrative practicals • basic skills practicals	• discussion • didactic teaching • active learning using text • presentations • use of secondhand data • evaluating investigations

Figure 1 A simple typology distinguishing the 'what to teach' and the 'how it might be taught'

learning demand (Leach & Scott, 1995) than those which simply aim to allow students to see and remember an observable event. In such activities, students are likely to require assistance to use or develop the ideas that make sense of the activity, and lead to learning. Activities that have this kind of 'scaffolding' built into their design are likely to be more effective than ones which do not.

It is widely assumed that doing practical work enables both the substantive ideas and ideas about evidence to be addressed. After all, when scientists solve problems they apply their understanding of both the substantive ideas and their understanding about validity and reliability to solve their particular problem, so why should school science not mimic this? What this argument fails to distinguish is the educational purpose of different practicals:

Practical activities differ considerably in what they ask students to do and what they are trying to teach. If we are interested in the effectiveness of practical work, we really have to consider specific practical activities that we use, or plan to use. (Millar, 2009: 1)

Much of the practical work used by schools is 'illustrative' in nature; that is, it is designed specifically to show pupils a particular science phenomenon and, as such, it has a very different purpose compared with what scientists do, which is to solve problems for which there is no known solution. Problem solving with open-ended enquiries has its place in the school curriculum (to which we return later) as a means by which pupils can creatively apply their understanding, but first we need to consider the illustrative practicals we use to teach them the ideas that they will then be able to apply.

The new National Curriculum instructs that '*Working scientifically… must always be taught through and clearly related to substantive science content*'. Can a practical designed to illustrate a substantive phenomenon also be used to illustrate the ideas behind '*Working scientifically*'? Does one size fit all?

Recent research (Abrahams and Millar, 2008) into teachers' focus during practical work teaching indicates that very little emphasis is placed on the opportunities for pupils to develop their understanding of evidence. We contend that if a practical was designed primarily to address substantive ideas (as the principal learning objective of the activity) – as all of those observed in their research were – this is not surprising. From our experience, there are two main reasons for this:

- it is very difficult (for teachers and pupils) to focus on developing an understanding of both substantive ideas and evidence at the same time;
- practicals designed to help pupils focus on 'theory' are specifically established to eliminate many of the issues about evidence that we need to teach (Box 1) because almost all of the decisions have already been made.

For example, a simple practical to illustrate a substantive phenomenon, such as how the rate

BOX 1 The ideas about evidence in the Methods section of Hunt (2010: 5–6)

The design of experiments and investigations

The ideas

- Changes in technologies for observation and measurement can increase the range of types of question that can be investigated by science.
- An investigation is an attempt to determine whether or not there is a relationship between variables.
- An investigation is valid if it is designed to answer the questions being asked.
- Variables may be continuous, discrete, or categoric.
- Laboratory investigations study how changing one independent/input variable (factor) affects the dependent/output variable (outcome) while all other variables are kept constant (controlled).
- In field investigations many naturally changing variables are measured. As far as possible, the aim is to ensure that variables that change their value do so in the same way for all measurements of the dependent variable.
- In many situations, scientists systematically observe or measure a sample of the objects or cases they are studying. Samples can be composed of repeated readings of an event or of specimens. The greater the number of readings in a sample, the more likely they are to be representative of the target population or the event in general, and the more is known about the population from which the sample is drawn.
- Control groups are often used in biological and medical research to investigate a claim that a factor increases the chance (or probability) of an outcome. Control groups ensure that observed effects are due to changes in the independent variable alone. A control group is matched with the experimental group on as many other factors as possible, or is chosen randomly so that other factors are equally likely in both groups. The larger the groups, the more confident scientists can be about any conclusions.
- Human expectations can influence the outcomes of clinical trials. Precautions are taken to prevent this. In a blind trial each individual does not know if he or she is in the treatment group or the control group. The trial is double blind if the person who measures the outcomes also does not know this.

Making measurements

The ideas

- A measurement is valid if it measures what it is supposed to be measuring.
- Measuring instruments are calibrated to establish the relationship between the readings (indications) and the variable being measured.
- The selection of measuring instruments should attempt to minimise uncertainty and has to take into account their sensitivity and their resolution.
- Several measurements of any quantity are likely to vary.
- An accurate measurement is one that is close to the true value.
- Measurements are precise if the values cluster closely.
- A measurement is repeatable when repetition, under the same conditions by the same investigators, gives similar results.
- A measurement is reproducible if similar results are obtained by different investigators with different methods or equipment.
- Measurement error is the difference between the measured value and the true value.
- All measurements are affected by random error due to results varying in an unpredictable way from one measurement to the next. The effect of random variation can be reduced by making more measurements and reporting a mean.
- Systematic error is due to measurement results differing from the true value by a consistent amount each time. One cause of systematic error is a zero error in a measuring instrument.

Presenting and evaluating data

The ideas

- Data can be presented as tables, bar charts, line graphs, scattergrams, histograms and pie charts. The optimum method of presentation depends on the nature of the data.
- The mean of several repeat measurements is a good estimate of the true value of the quantity being measured.
- From a set of repeated measurements of a quantity, it is possible to estimate a range within which the true value probably lies.
- If a measurement lies well outside the range within which the others in a set of repeats lie, or is off a graph line on which the others lie, this is a sign that it may be incorrect. If possible, it should be checked. If not, it should be used unless there is a specific reason to doubt its accuracy.
- A valid conclusion is one supported by valid data, obtained from an appropriate experimental design and based on sound reasoning.
- The degree of confidence in conclusions is a judgement of the extent to which the conclusion is justified by the quality of the evidence.
- Scientists make, preserve and study collections of specimens as valuable sources of information which can help to answer important questions. The same set of objects can be classified in

BOX 1 (*continued*)

different ways; the classification used depends on the purpose of classifying, and is often based on underlying theoretical ideas about the objects.

Looking for patterns and relationships in data

The ideas

- If an outcome occurs when a specific factor is present, but does not when it is absent, or if an outcome variable increases (or decreases) steadily as an input variable increases, we say that there is a correlation between the two.
- On a graph, a relationship can show as a line or curve. The relationships that exist between variables can be linear (positive or negative), it may also be directly proportional.
- In some situations, a factor alters the chance (or probability) of an outcome, but does not invariably lead to it. We also call this a correlation.
- A correlation between a factor and an outcome does not necessarily mean that the factor causes the outcome; both might, for example, be caused by some other factor.
- Even when there is evidence that a factor is correlated with an outcome, scientists are unlikely to accept that it is a cause of the outcome, unless they can think of a plausible mechanism linking the two.

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of cooling affects the size of crystals formed (see the protocols developed by the Royal Society of Chemistry), has been designed specifically so that the pupils' focus is directed to the substantive ideas illustrated through the practical's designers selecting substances that show a clear outcome when cooled to temperatures found in the lab; where repeated readings are unnecessary since the trend is clear; and where ideas to do with the quality of the measurements are not an issue. Of course, there *are* opportunities, when teaching practicals that illustrate substantive ideas, to address the ideas about evidence but Abrahams and Millar's (2008) research shows that many such opportunities are missed.

So how can we use practicals to illustrate ideas about evidence? One way to do this is to devise practicals that illustrate and have learning about evidence as their specific learning objective. But what would practicals that have this aim look like?

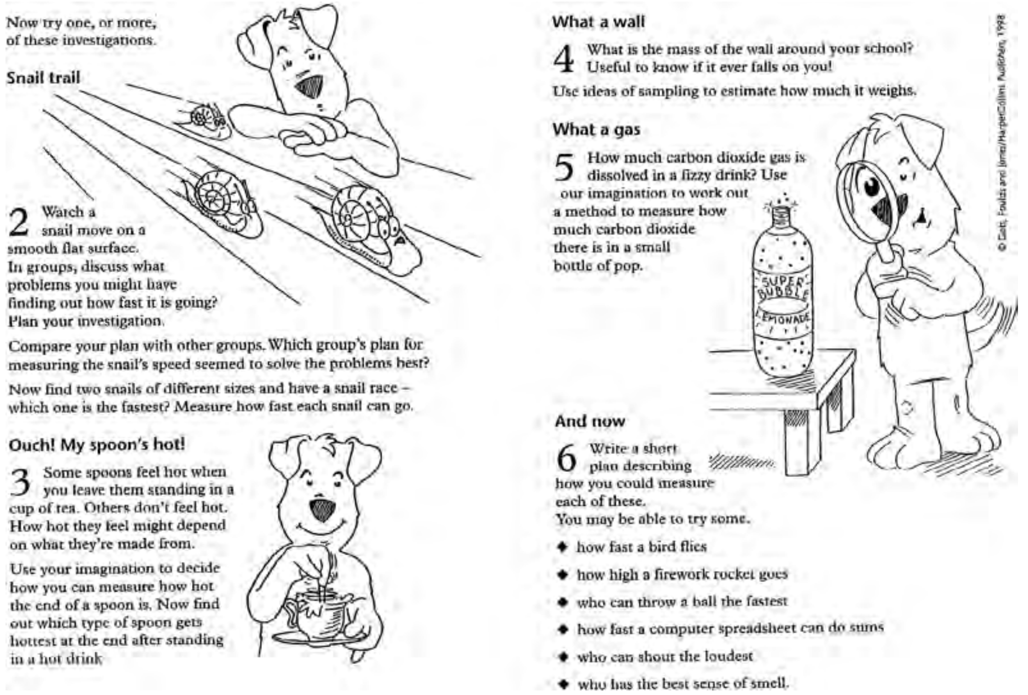
Practicals that help pupils develop their understanding of evidence

Practicals that are designed to illustrate clearly the substantive phenomena tend to have already addressed the issues that students need to understand about evidence (Box 1). The pattern in the data to illustrate the substantive phenomena is clear since the practical's designer has, through extensive trialling and experience, determined the conditions required to show the phenomenon clearly (by ensuring that the range of values selected for the independent variable enable a clear difference to be seen in the dependent variable) and has significantly reduced any variation in the data that might otherwise have masked the pattern (owing to careful design and control of variables, through the selection of good measuring instruments and by the selection of samples with limited variation).

One way in which practical work can be used to illustrate the ideas behind '*Working scientifically*' is to let pupils experience problems for themselves. Figures 2 and 3 show some examples. If pupils are involved in the planning, generation and handling of 'messy data', they recognise, with scaffolded support using non-practical activities as well, that patterns are hard to determine from such data. Working outside the classroom presents many such opportunities.

Through hands-on generation of such messy data, pupils are better able to identify and be explicitly taught about the ideas in Box 1. Our research shows that discussion and other non-practical activities that focus on the ideas of evidence, at key points in the practical, enable the learners to grapple with the issues affecting the quality of the work. If these ideas are addressed systematically, pupils can learn the basis of decision-making during whole and parts of investigations, applying their understanding to help to improve the quality of the data and to make claims from data that are not as clear-cut as the contrived experiments that they are usually presented with and that have the illustration of substantive ideas as their focus.

We find that if the context of the investigation is one in which the pupils are unaware of 'a right answer' then their focus is more directed to the quality of the evidence. Since the nature of much



Now try one, or more, of these investigations.

Snail trail

2 Watch a snail move on a smooth flat surface. In groups, discuss what problems you might have finding out how fast it is going? Plan your investigation.

Compare your plan with other groups. Which group's plan for measuring the snail's speed seemed to solve the problems best?

Now find two snails of different sizes and have a snail race – which one is the fastest? Measure how fast each snail can go.

Ouch! My spoon's hot!

3 Some spoons feel hot when you leave them standing in a cup of tea. Others don't feel hot. How hot they feel might depend on what they're made from.

Use your imagination to decide how you can measure how hot the end of a spoon is. Now find out which type of spoon gets hottest at the end after standing in a hot drink.

What a wall

4 What is the mass of the wall around your school? Useful to know if it ever falls on you!

Use ideas of sampling to estimate how much it weighs.

What a gas

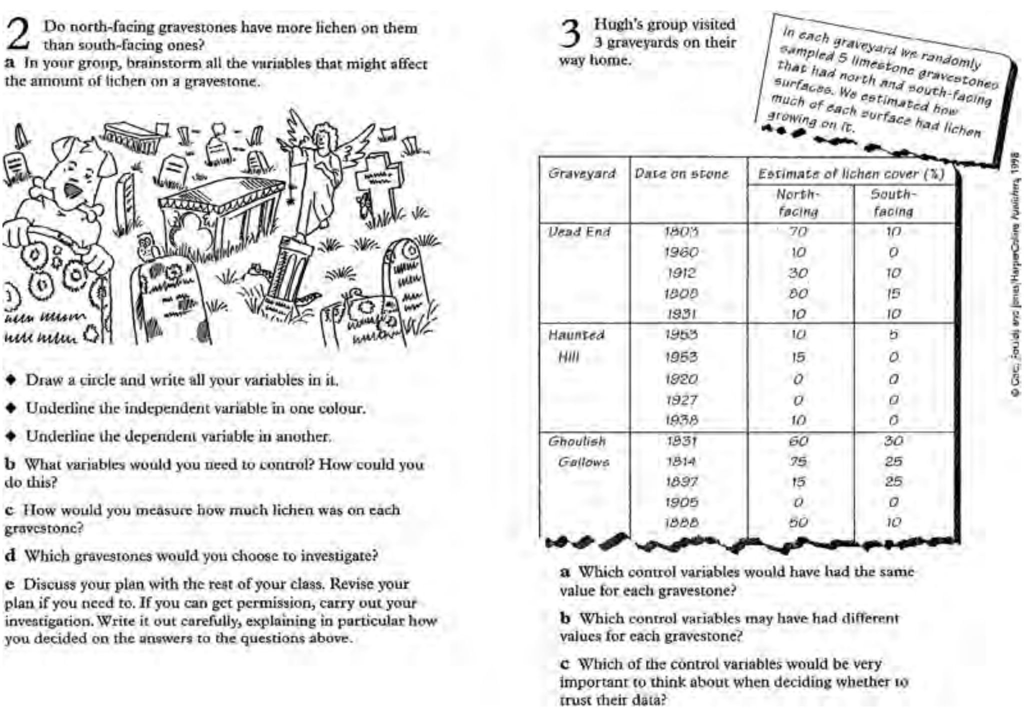
5 How much carbon dioxide gas is dissolved in a fizzy drink? Use our imagination to work out a method to measure how much carbon dioxide there is in a small bottle of pop.

And now

6 Write a short plan describing how you could measure each of these. You may be able to try some.

- how fast a bird flies
- how high a firework rocket goes
- who can throw a ball the fastest
- how fast a computer spreadsheet can do sums
- who can shout the loudest
- who has the best sense of smell.

Figure 2 Scaffolded practical activities that focus on measurement; from Gott *et al*. (1998: 28)



2 Do north-facing gravestones have more lichen on them than south-facing ones?

a In your group, brainstorm all the variables that might affect the amount of lichen on a gravestone.

- Draw a circle and write all your variables in it.
- Underline the independent variable in one colour.
- Underline the dependent variable in another.

b What variables would you need to control? How could you do this?

c How would you measure how much lichen was on each gravestone?

d Which gravestones would you choose to investigate?

e Discuss your plan with the rest of your class. Revise your plan if you need to. If you can get permission, carry out your investigation. Write it out carefully, explaining in particular how you decided on the answers to the questions above.

3 Hugh's group visited 3 graveyards on their way home.

In each graveyard we randomly sampled 5 limestone gravestones that had north and south-facing surfaces. We estimated how much of each surface had lichen growing on it.

Graveyard	Date on stone	Estimate of lichen cover (%)	
		North-facing	South-facing
Dead End	1803	70	10
	1960	10	0
	1912	30	10
	1800	80	15
	1931	10	10
Haunted Hill	1953	10	5
	1953	15	0
	1920	0	0
	1927	0	0
	1938	10	0
Ghoulish Gallows	1931	60	30
	1814	75	25
	1897	15	25
	1905	0	0
	1888	50	10

a Which control variables would have had the same value for each gravestone?

b Which control variables may have had different values for each gravestone?

c Which of the control variables would be very important to think about when deciding whether to trust their data?

Figure 3 Scaffolded practical activities that focus on validity of design and control variables in fieldwork; from Gott *et al*. (1998: 24) pupil fieldwork results in messy data and, owing to its nature, pupils seldom expect it 'to work' or clearly illustrate the 'textbook' substantive ideas, outdoor learning also provides opportunities to focus on ideas of evidence (Lambert and Reiss, 2014).

Everyday examples are good starting points for teaching many important ideas, and teachers can focus the pupils' learning accordingly. For instance, while an exploration of the factors that affect the 'quantity of bubbles' produced by bubble bath enables pupils to investigate many different relationships and to trial different values of the control variables to determine sensible values, this is a great practical for pupils to be asked to consider how the dependent variable, the 'quantity of bubbles', can be defined (depth or volume or surface area?) and measured and how these decisions affect the validity and reliability of the investigation.

Other practicals (set in contexts where the substantive knowledge is not the focus or is not too demanding on the pupil) that enable teachers to focus pupils' learning on ideas about evidence include the following.

- Asking pupils to determine a means to measure the absorbency of a paper towel introduces pupils to important ideas about the causes of variation in repeated readings, the quality of measuring instruments and variation in a sample (Campbell, 2010).
- Investigating the relationship between the mass hanging and then released from a 'springboard' (a ruler hanging over a bench) and the 'jump height' of a toy figure propelled from the springboard can be used to discuss: the suitability of the range and interval of the independent variable; the identification of and determination of the values for the control variables; sources of uncertainty in measurements; and that the underlying relationship can, in itself, be employed as a measuring instrument for unknown masses (Gott and Roberts, 2008).
- Comparing sampling techniques in the field to see how any inherent variation is 'captured' in samples (a sample of 'pooh-stick' readings of a stream's flow; a sample of daisy plants on the hockey pitch), and considering the consequences on an investigation's claims, can draw pupils' attention to ideas that are seldom addressed in lab-based investigations (Campbell, 2010).

Once pupils have been taught ideas about evidence, they are able to apply this – with understanding, rather than just routinely 'copying' other examples – in their own enquiries. This creative application of ideas to solve a problem is, in our experience, engaging and motivating – it is both 'hands-on and minds-on' (Millar, 2009).

Putting it all together

'*Working scientifically*' involves pupils applying their understanding of evidence to explore scientific issues. For pupils to be able to apply their understanding of evidence, contexts that do not place too many substantive knowledge demands on the pupil work best in our experience. Having an open-ended context, in which the pupil does not already know the route to a solution and does not have a particular 'right answer' in mind, provides such opportunities. Box 2 contains some examples that fit these criteria.

'*Working scientifically… taught through and clearly related to substantive science content*': the big challenge

We have seen so far that '*Working scientifically*' is underpinned by an understanding of evidence and that this understanding can be specified (Box 1). Understanding evidence, just like understanding any other concepts in science, requires that pupils are taught the ideas so that they can construct meaningful learning. In our experience, pupils need time to develop this 'joined-up' thinking and we have found that engagement with the type of practical work where pupils are confronted with decisions that require this thinking helps develop such meaningful learning.

Practicals designed to illustrate the ideas of science differ in their nature depending on whether their focus is on pupils' understanding of the substantive ideas of science or the ideas of evidence. Practicals designed to illustrate substantive ideas are not the best activity necessarily to teach about evidence. Practicals that have an understanding of evidence as their focus are best designed with no 'right answer' and low substantive demand. Thus the instruction that '*Working scientifically*' should be taught with clear links to the substantive content needs

BOX 2 Applying the science; from Gott *et al*. (1999)

- How does the angle of the slope needed to tip a bottle over vary with how full the bottle is?
- Do free range eggs have more calcium carbonate in their shells than battery-farm eggs?
- Do taller trees have more fruit than smaller ones?
- If you spin an egg, can you tell how long it has been boiled for?
- Do indigestion tablets work faster crushed or whole?
- Can bigger rafts hold more weight than smaller ones?
- How is the force used to raise a barrier affected by the mass of the 'counterweight'?
- What's the best way to get sweet-pea seeds to germinate?
- Where's the best place to take a plant cutting – above or below the leaf joint?
- Which chemical is best used to absorb water from the air?
- How does the angle of the feathers affect how fast a shuttlecock falls?
- Is there a relationship between the amount of dandelion above ground and its root length?
- How is the rate of reaction between citric acid and calcium carbonate affected by the amount of water used?
- Which dissolves lime-scale faster – vinegar or hydrochloric acid?
- Do biological washing powders really work better at low temperatures?

to be interpreted with care, and is a challenge to curriculum developers and teachers.

The challenge is therefore:

- to plan a curriculum that enables a progression in pupils' understanding of the ideas of evidence;
- to 'map' this across the progression planned for the substantive content and the school's teaching sequence;
- to include practical activities within this sequence that have as their focus the illustration or application of the ideas of evidence.

This will be no easy task. There are relatively few resources that support such a learning progression, so curriculum developers and teachers will need to consider carefully how best to address this. Millar's (2009) *Practical Activity Analysis Inventory (PAAI)* may be a useful tool for thinking about the practicals used when teaching '*Working scientifically*'; do the practicals enable pupils to meet the learning objectives of understanding evidence whatever practical approach is used?

In '*Working scientifically*', pupils need to be taught so that they develop an *understanding* of the nature, processes and methods of science while teaching through the substantive content of the curriculum. Failure to rise to this challenge could mean that the new curriculum's good intentions are in danger of being lost.

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