Using different types of practical within a problem-solving model of science

Ros Roberts

A framework for thinking about the role of practical work in science teaching

Investigative work was introduced in 1989 as part of the English National Curriculum, science attainment target 1 (Sc1) (DES, 1989), since when it has been a cause of much concern amongst both teachers and researchers. In some schools, Sc1 investigations seem to have become almost synonymous with practical work in science and in some textbooks almost any activity that uses apparatus seems to be called an investigation! The recent House of Commons Science and Technology Committee report (2002) castigated practical work in general as being something that:

> *students see little point in carrying out ... where they already know the result and are just expected to follow instructions to reach that end. (p. 20)*

But practical work, which comes in many guises, can be much more than the assessment-driven practicals of the National Curriculum. The purpose of this article is to show how different types of practical can be used within a model of science as a problem-solving activity, which will allow judgements to be made about what sorts of practical we should be considering.

ABSTRACT
This article considers the role of different types of practical work in school science. It illustrates a model of science as a problem-solving activity, which requires an understanding of both the substantive and procedural ideas of science. Different types of practical are then located within the problem-solving model. The resultant analysis can be used to inform decisions about the appropriateness of different types of practical work.

Justifications for practical work

The first point to make is that practical work is a means to an end; it is not an end in itself, any more than discussion or debate are ends. Practical work is just one of many ways of teaching science. So the most basic of questions is: What is to be learned and is practical work a good teaching method for this?

There are numerous justifications for using practical work in our teaching, which recognise its value as more than just a means of teaching ideas. Various classifications have been put forward over the years. Kerr (1964) identified ten aims from a large survey of practice. Woolnough and Allsop (1985) reduced this to three fundamental aims:

- developing practical skills and techniques;
- being a problem-solving scientist;
- getting a 'feel for phenomena'.

Wellington (1998) considered the rationales presented in the literature and grouped them under three broad headings:

- cognitive arguments (about understanding, visualising, illustrating/affirming theory);
- affective arguments (to do with motivating, exciting, helping to remember);
- skills arguments (learning manual dexterity, as well as 'higher level' activities such as observation, measurement, prediction, inference).

As noted later in this article, there is not much good evidence that practical work actually meets all these aims. However, in my view, practical work can provide much to interest and stimulate both pupils and teachers. This article will consider how different types of practical can be used to teach the ideas and skills required to solve problems in science. But what kind of practical work could be used?

Types of practical

There are many ways of typifying different practical activities. For instance, Woolnough and Allsop (1985) considered there to be three main types: exercises, investigations and experiences. Millar (1989) criticised these as not including practicals that are illustrative of substantive ideas in science, used to refine or check the 'theory'. Wellington (1994) included ways in which practicals could be organised in the classroom in his typology; i.e. demonstrations, class experiments, circus of activities, simulations and role plays as well as investigations and problem-solving activities.

For the purposes of this analysis, five different types of practical are considered, each of which has, or could be adjusted to have, a particular emphasis. These are obviously not hard and fast categories but are considered good enough for the purposes of this analysis.

Skill practicals

These are practicals that teach and train pupils in scientific skills, which could range from simple ones such as reading instruments or heating a test-tube safely, to following complex protocols such as preparing and staining a microscope slide, setting up a potometer or calibrating an oxygen probe. They are distinguished as skills because they require practice of a protocol. These skills are useful. In some science-based work, including nursing (Aikenhead, 2003) and lab-based contexts (Gott, Duggan and Johnson, 1999), the recall of skills and complex protocols seems to be an important part of the work.

Observation tasks

Different forms of observation task can have different demands. Many used at school level require recall of ideas and basic skills and really act as illustrative practicals (see below).

However, it is worth noting that observation is more than seeing. It is a crucial window on the everyday world through which science can be seen 'in action'. For instance, roads wear particularly badly on corners. 'Observing' through a conceptual window of force and friction, we can see that the centripetal force needed for cars to corner results in stress on the road surface and accelerated wear and tear. That is a much richer 'seeing' that does not seem to be encompassed within most observation tasks and involves the application of substantive ideas to real contexts. The observation task can be a way of showing how experimental science has its roots in careful, concept-driven viewing of the real world.

'Technological' tasks

There are some practicals that largely depend on logical reasoning and recall of substantive ideas. At the simplest level these might include identifying faulty components within a simple electric circuit. More complex ideas and thinking are applied to situations such as designing electronics solutions or logical tasks such as identifying a chemical through a series of tests. Construction of a pond could be considered to be a 'technological' task too: ecological ideas are recalled and applied in a logical way. Technological tasks may require complex recall of skills and protocols as well as the application of ideas to new contexts and logical thought.

Investigations and exploratory tasks

These are practicals which consider a problem for which there is no easily recalled solution. From my experience, and that of the House of Commons report (2002), Sc1 'investigations' seldom fit this definition! It could be argued that, for many pupils, Sc1 assessments have become little more than recalling complex routines. In effect they could be thought of as skills practicals: complex protocols to be applied to different routine contexts, such as enzymes, electric circuits or rates of reaction, that require little understanding or consequent decision making.

Investigations and exploratory tasks differ in practice largely in their scope and have been considered together here because of their open-ended nature. In recent National Curriculum contexts an investigation has been defined as a problem that is restricted to considering relationships between variables. Investigations are usually relatively short, focused tasks that could be completed in a couple of lessons. Exploratory tasks are also open-ended with no easily recalled solution; they explore more extended problems and are not restricted to just the relationship between (usually) two variables (which is how 'an investigation' has come to be defined). The task may be something like a series of linked investigations within a topic, or a survey which considers many variables at the same time. Such practicals are perhaps familiar to those working on Nuffield A-level schemes. They involve the use of both substantive concepts and procedural ideas in a complex task or series of tasks rather than being a particular focused problem to solve.

There is evidence from work done by pupils in out-of-school contexts, such as CREST awards and science clubs and competitions where pupils are allowed to carry out 'free format' explorations (Tytler and Swatton, 1992; Woolnough, 1998), that demonstrates that the scope of genuine open-ended enquiry is within the capabilities of some pupils. Exploratory tasks allow pupils to be creative. While pupils recall skills and sometimes modify protocols with which they are familiar, they also invent new ways to get around practical problems, apply ideas to new contexts and synthesise the substantive and procedural ideas to solve the problem and analyse the data to evaluate the evidence.

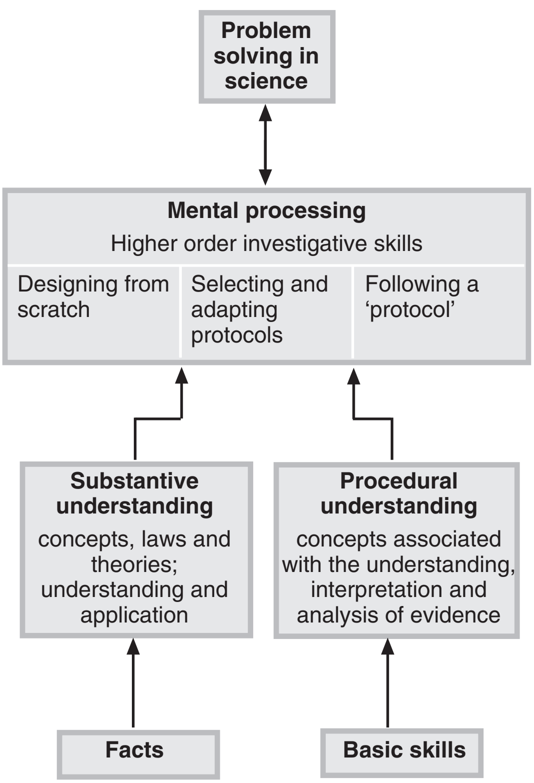

Figure 1 The content-based demands of a problem-solving model for science.

Illustrative experiments

Any of these types of practical can act as illustrations – either for pupils to do by following complex protocols or for teachers to demonstrate. The emphasis is then at the discretion of the teacher who can bring out substantive or procedural ideas as they see fit in that particular context.

What is to be learned?

Wellington's (1998) 'affective' arguments for practical work are important and seem to apply, at least in principle, to any type of practical work. This discussion is therefore going to focus on the ideas that might be learned in different types of practical work. The view is taken here that practical science, ultimately, is about solving problems, be that to create new knowledge, to answer empirical questions, to make something or to make that something work. Gott and Mashiter (1991) proposed a model for problem-solving in science which I have modified (Figure 1). The diagram presents a pared down model of the content-based demands of science. It is intended, quite deliberately, to act as a skeleton for development and *not* an all-encompassing model.

In this model, solving a problem in science requires a synthesis of two sets of understandings, each with its own knowledge base: a substantive understanding (such as the concept of a force or the theory of natural selection) and an understanding of the ideas required to interpret and analyse evidence – a procedural understanding. The 'mental processing' involved in putting the ideas together in the scientist's head may vary according to the context of the problem. For instance, sometimes the problem being solved is so similar to previous problems that familiarity with the ideas and approach used means that minimal decision-making is required and in effect the scientist is following a 'protocol'. In solving completely novel problems, the solution may be designed from scratch, drawing on skills, substantive ideas and procedural ideas in a far more complex way. In many situations, past experience enables the scientist to select and adapt previously conducted protocols, which seems to be intermediate to these other extremes.

An illustration of how the elements of the model might be used when solving a problem in science is given below, with reference to a particular field investigation in biology.

Freshwater shrimps – an exploration

This example of an extended exploration is intended to illustrate the elements of practical problem-solving in science in relation to the model (Figure 1). The way in which elements from the model are used to solve a problem are described in relation to a context that is not constrained by the current Sc1 assessment criteria: the distribution of freshwater shrimps in a stream. The analysis is structured according to the main ideas being used at each stage of the exploration, which can then be located on the model.

Substantive understanding: ***observation, identification, adaptation and niche***

Imagine we are paddling in a stream. We might start to notice and identify many different animals: mayfly and caddis fly larvae, freshwater shrimp, various worms, snails, freshwater mussels and limpets, little fish, etc. We observe that different things are found in different numbers in different places. It is through ideas about adaptation of organisms and the concept of a niche that we might hypothesise that different organisms are likely to be found in different environmental conditions. It is a direct application of substantive understanding and, what is more, a key link between theory and the real world it attempts to explain. We could ask ourselves: What factors might affect the number of freshwater shrimp? The answers to this would draw on our substantive knowledge base and would inform the design of any experiment.

Procedural and substantive understanding: ***identification of independent variables***

It would then be time to turn the hypothesis into something that could be tested. We'd now need to use both procedural and substantive understanding related to the structure of an investigation. The selection of which independent variables to consider would largely be determined by our substantive understanding: either ideas which are already in our heads or by referring to what other scientists have already found out. For instance, we probably wouldn't consider things like the political party in charge of the local council or the star sign of the farmer whose land we are on, because we have no theory in our heads to suggest that these have any influence on the number of shrimp in different places! But we might also, wrongly, dismiss another variable that could ultimately be important because of our *lack* of understanding.

A substantive understanding of shrimps' need for dissolved oxygen and of adaptations that prevent them being washed downstream might suggest that water speed and depth are worth considering. Similarly, knowing that different organisms can tolerate different size of substrate, we might decide to record whether they are found in silty areas or where there are boulders. Since shrimps are largely detritivores, we could decide that identifying the vegetation surrounding or further up the stream might also be important. These decisions are determined largely by an understanding of biotic and abiotic factors affecting animal distribution.

Procedural understanding: ***measurement validity and reliability – how to measure the number of shrimps***

How might we find out how many shrimp there are in a given area – the dependent variable? The method we choose would affect the quality of the data collected. We may recall a technique called 'kick sampling' – not the most environmentally friendly sampling method available but we might decide that two minutes should dislodge most of the shrimps to give a measure (a sample) in proportion to the total population. Our decision to do this for two minutes is a compromise between getting a reasonably good estimate and dislodging every last shrimp. Since the shrimp are easy to identify and count, we work on the assumption that our counts will be reliable enough. Judgements about the quality of the data collected by this technique require an understanding of the concept of reliability and its application in relation to the actual data collected; in this case, this is the likelihood that if we *could* repeat the measurement we would dislodge more or less the same number.

Procedural understanding: ***selection of appropriate instruments***

Each independent variable would need to be measured. Decision time! Would 'Pooh sticks' give a good enough measure of flow rate or should an electronic flow meter be used? Is a metre rule marked in centimetres good enough to measure the depth of the water? Is the thermometer accurate enough? If a previously followed protocol is not driving the decisions we are making, then trials to evaluate the instruments and determine which are 'good enough' might be required. Again, the validity of the instruments and the reliability of the data would need to be judged in relation to the actual data that are collected. In practice this means that, without prior experience from similarly followed protocols, it is almost impossible to plan an investigation without trying out the apparatus and techniques available – planning is part of an iterative process, where evaluations are constantly being made in response to the data collected.

Skills: ***practical techniques, following protocols and recording skills***
At each site we might follow instructions or recall skills about how each measurement should be taken: How long should the thermometer be kept in the water for? Has the oxygen probe been set up and calibrated properly? We might decide to record the number of shrimp at each site and each site's environmental data systematically in a table, using skills we've developed in other practicals.

Procedural understanding: ***variable types, range and interval of the independent variables, sampling issues and the number of readings***
Recognising that we need to have readings from sites that include a range of independent variable values draws on a procedural understanding as well as decisions about safety – it might be too fast flowing or deep to get all the readings we might want safely. A decision also has to be made about how many sites should be sampled (to account for the inherently varied distribution of the shrimp population as well as to ensure that sufficient data have been collected in places where there are different values of the independent variables) and whether repeated readings are necessary at each site. Again, these decisions are made iteratively – we can't pre-judge the number of repeats we'll have to do since we don't know how the shrimp numbers differ at each site (if at all) and therefore how much data is required to be confident about seeing differences if they exist.

Procedural understanding: ***looking for relationships between variables, validity of variable structure, determining the strength of the relationship*** **and Skills:** ***graphing and statistical techniques***
Having collected sufficient data, we need to consider each independent variable in turn, to see whether there is a relationship between it and the number of shrimp. The most valid relationships are determined by considering associations where values of other key variables have a similar value. So, we might want to consider the relationship between shrimp numbers and flow rate only in areas where the predominant surrounding vegetation is, say, mountain ash trees. Deciding on the appropriate way to present the data and selecting a valid statistical test for analysing the data will draw on our procedural understanding, while actually plotting the data and using the statistical techniques will involve recall of skills and procedures practised before.

Substantive and procedural understanding: ***drawing conclusions***
Determining what we might conclude from the data collected requires an evaluation of the whole task with respect to the procedural knowledge base: How reliable are the data? Is the overall investigation valid? Conclusions also need to be checked against what is already known about shrimps and factors affecting organisms' distribution – the substantive knowledge base.

Summary

The shrimp scenario illustrates how different elements of an extended problem-solving task draw on all the different ideas within the model (Figure 1) and with different levels of demand, depending on exactly how the problem is solved. The procedural ideas used in this task comprise a knowledge base, ideas that can be learned and applied in the exploration. The skills and ideas, both procedural and substantive, within the model could then legitimately be considered as the basis for the curriculum. This leads us back to the question of how.

Types of practical related to the problem-solving model

Opportunities to carry out this sort of extended task, which incorporates all the elements from the problem-solving model, are unfortunately all too rare. And they place considerable demands on all concerned. But, even if it is unrealistic to enable all pupils to carry out extended explorations it is still possible to teach all elements from the model using smaller, more manageable practical tasks, as shown in Figure 2. Within each of the different types of practicals we can focus on different elements of the model. Pupils can be taught all of the elements required for problem-solving through these smaller targeted practicals. That does not of course guarantee that they can put all these ideas together successfully in a longer exploration. For instance, pupils could carry out parts of an investigation, such as determining an appropriate

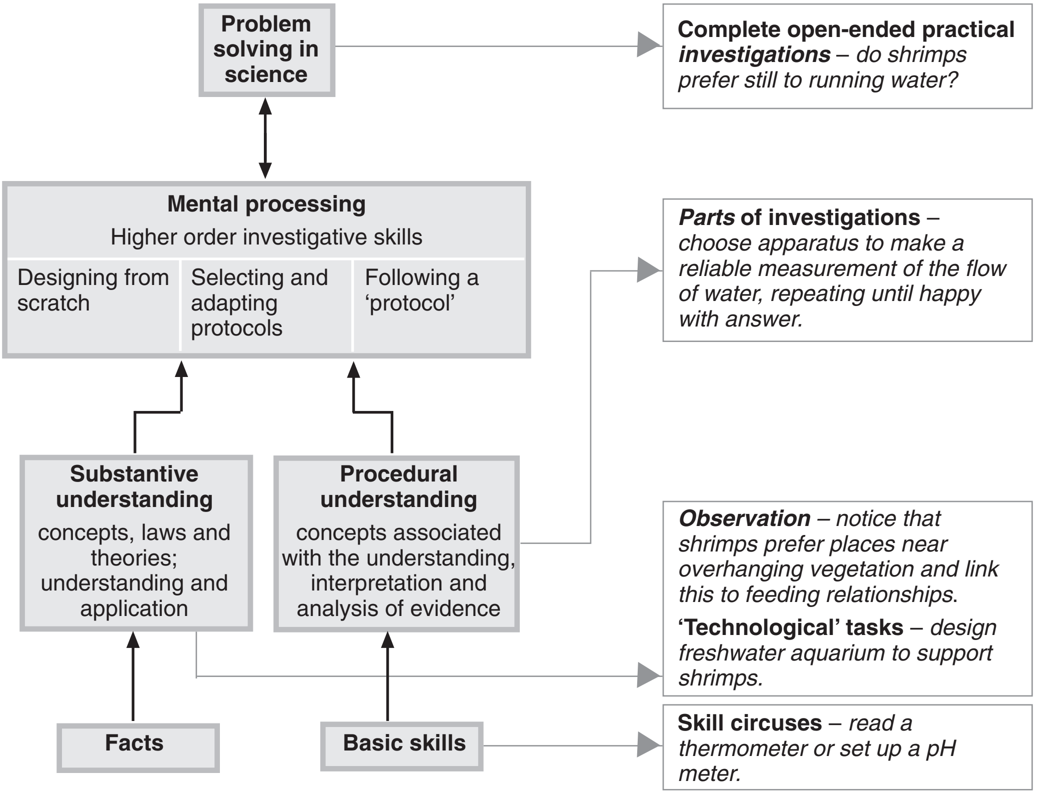

Figure 2 Types of practical work related to the problem-solving model.

sampling method for estimating the number of daisies on the school field; or they could do an illustrative experiment that follows a protocol involving feeding preferences and choice chambers, with the aim of learning both the procedural ideas of sample size as well as the substantive ideas of feeding relationships and niche. These ideas could then be used within the context of a full investigation or exploration.

Since illustrative practicals could be used as a teaching activity for any of these ideas, they are not included specifically on the figure. Exploratory practicals are represented by the figure *as a whole.* Looked at in this way, we can see that these different types of practical are not in any sense in competition. They form part of a coherent holistic problem-solving approach to practical work in science which, if kept in mind, can act as a guide to choosing tasks such that the end-point is a rounded understanding of practical problem-solving.

We can see that different practicals can be used to teach different things. What teaching approach we choose, and for whom, then becomes an empirical question. What works for the aims required?

Illustrative practicals have been researched and evidence largely points to them being ineffective, at least at teaching understanding of the substantive ideas (Watson, Prieto and Dillon, 1995); this is also evident from some of the comments in the House of Commons report (2002). There is a view (Duveen, Scott and Solomon, 1993; Wellington, 1998) that if experiments simply 'go wrong' their educative value is diminished if not negative. We know very little about the effectiveness, at least in terms of pupils' understanding, of other types of practical. However, most would agree that pupils enjoy practical work (Campbell and Wilson, 1998; Wilkinson and Ward, 1997).

This sounds negative but it is not intended to be. There is much to interest and stimulate pupils and teachers in good varied practical work. To limit ourselves to one type would be nonsensical: all of them have something to offer but we need to be clear as to what we are hoping pupils will learn from the experience and choose accordingly.

Conclusion

If we think that extended explorations, open-ended problems with no easily recalled solutions, are the 'ideal goal' of practical work, then it is obvious that pupils will not be able to do many of these in an overcrowded curriculum. We therefore need to break them down into manageable chunks. The illustration of the shrimp scenario shows how each of the elements of an exploration can be located within the problem-solving model and Figure 2 shows how these elements can be taught using different types of practical.

Different types of practical are shown to be in no sense in competition with each other: one type is no better than another. They complement each other in this broader problem-solving view.

Teachers are in the best position to decide the sequencing of ideas, as well as when and how they should be taught in their class. As we can see, there's a place for all sorts of practical activity in the class (and outside!).

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