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The role of practical work in the teaching and learning of science

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1 Introduction

The purpose of this paper is to explore and discuss the role of practical work in the teaching and learning of science at school level. It may be useful to begin with some general remarks about science and science education, to clarify the perspectives which the paper adopts.

The term 'science' can be used to refer to a *product* (a body of knowledge), a *process* (a way of conducting enquiry) and an *enterprise* (the institutionalised pursuit of knowledge of the material world[1]). The distinctive characteristic of scientific knowledge is that it provides material explanations for the behaviour of the material world, that is, explanations in terms of the entities that make up that world and their properties. Through its choice of questions to address and the kinds of answers to accept, its methods of enquiry, and its procedures for testing and scrutinising knowledge claims, the scientific community has succeeded in building up a body of knowledge which is consensually accepted by that community. Whilst this is always open to revision, its core elements are stable and beyond reasonable doubt. We value science because of its success in explaining phenomena in elegant and parsimonious ways, which are intellectually satisfying and which often facilitate the purposeful manipulation of objects, materials and events.

The aims of science education might then be summarised as:

- to help students to gain an understanding of as much of the established body of scientific knowledge as is appropriate to their needs, interests and capacities;
- to develop students' understanding of the methods by which this knowledge has been gained, and our grounds for confidence in it (knowledge *about* science).

The second of these is often referred to as 'understanding the nature of science'. It includes an understanding of how scientific enquiry is conducted, of the different kinds of knowledge claims that scientists make, of the forms of reasoning that scientists use to link data and explanation, and of the role of the scientific community in checking and scrutinising knowledge claims. The two aims are closely inter-related. Indeed the second could be said to be entailed by the first: to claim to *know* something, it is not enough simply to believe it to be the case, but also necessary to have adequate evidence to support the claim. In other words, you have to be able to say not only *that* you think it is the case, but also *why*.

Additional reasons have been put forward by science educators for emphasising knowledge *about* science. First, a better understanding of the structure of scientific knowledge and the forms of argumentation used by scientists may help students to learn science content. Second, citizens in a modern society need some understanding of the nature of scientific knowledge in order to evaluate claims that may affect their everyday decisions (e.g. about health, diet, energy resource use) and to reach informed views on matters of public policy (e.g. genetic therapies, methods of electricity generation). Third, the characteristics of science as 'a way of knowing', and its 'institutional norms' of universalism, communalism, disinterestedness and organised scepticism (Merton, 1942), are of cultural (and moral) significance and

[1] 'World' here should be interpreted broadly; the subject matter of science is the material universe. 'Material' includes living matter.

value. These rationales reflect elements of both perspectives – the 'enlightenment perspective' and the 'critical perspective' – noted by Irwin (1995) in recent debates about scientific literacy and public understanding of science.

Whilst the two aims of science education above are closely inter-related, there is also a quite important difference between them. The first might be stated as bringing students' understandings closer to those of the scientific community. But it is rather harder to say whose ideas *about* science we wish to bring students' understandings closer to. Unlike scientific knowledge, where there is consensus about core knowledge claims, there is rather less agreement about the characteristic features of scientific enquiry and scientific reasoning. In one sense, professional scientists clearly know more 'about science' than any other group, but their knowledge is often largely tacit – 'knowledge in action' rather than declarative, propositional knowledge. The eminent philosopher of science, Imre Lakatos, once memorably commented of scientists' explicit knowledge of their practices that 'most scientists tend to understand little more *about* science than fish about hydrodynamics' (Lakatos, 1970: 148). But the views of philosophers of science also differ, as do those of science educators, certainly at the level of detail and perhaps more fundamentally. Furthermore, the questions that drive enquiry, and the methods of enquiry commonly used, vary across the sciences – so that generalisations about 'the nature of science' are rarely persuasive, and are often open to rather obvious objections. In thinking about this second aim of the school science curriculum, and the role of practical work in achieving it, it may be important to be clear as to whether we wish to promote a tacit 'knowledge-in-action' of science, or a more explicit, reflective and declarative knowledge.

It may also be important to distinguish, and keep in mind, that the school science curriculum in most countries has two distinct purposes. First, it aims to provide every young person with sufficient understanding of science to participate confidently and effectively in the modern world – a 'scientific literacy' aim. Second, advanced societies require a steady supply of new recruits to jobs requiring more detailed scientific knowledge and expertise; school science provides the foundations for more advanced study leading to such jobs. These two purposes may lead to different criteria for content selection, to different emphases, and (in the particular context of this paper) to different rationales for the use of practical work.

In this paper, 'practical work' means any teaching and learning activity which involves at some point the students in observing or manipulating real objects and materials. The term 'practical work' is used in preference to 'laboratory work' because location is not a salient feature in characterising this kind of activity. The observation or manipulation of objects could take place in a school laboratory, or in an out-of-school setting, such as the student's home or in the field (e.g. when studying aspects of biology or Earth science).

In section 2, I will discuss the implications of trying to integrate the two aims of science education into a seamless practice, pointing out some of the difficulties this raises. Sections 3 and 4 then discuss the role of practical work in relation to each of the two principal aims of science education identified above: developing students' scientific knowledge, and their knowledge about science.

2 Science as product and process – a seamless whole

The close interdependence of the two main aims of science education identified above has led many science educators to argue for a form of science education that combines and integrates them. The idea is that students are taught to carry out their own scientific enquiries and so acquire scientific knowledge for themselves. Clearly practical work has a central role in this vision of science education.

This idea of 'the pupil as scientist' underpinned the Nuffield Science Projects in the UK in the 1960s, which initiated a period of science curriculum innovation and reform that has continued to the present day. Though less prominent in later projects, it has remained an influential notion in the UK and elsewhere. It is not difficult to see why it is attractive to science educators. Encouraging students to pursue their own enquiries taps into their natural curiosity. Finding things out for yourself, through your own efforts, seems natural and developmental, rather than coercive, and may also help you to remember them better. It seems to offer a way of making evidence, rather than authority, the grounds for accepting knowledge. Indeed one of the great cultural claims of science is its potential as a liberating force – that the individual can and may, though his or her own interaction with the natural world, challenge established tradition or prejudice, by confronting it with evidence. An enquiry-based approach may also encourage students to be more independent and self-reliant. In this way it supports general educational goals such as the development of individuals' capacity for purposeful, autonomous action in the world.

As regards knowledge *about* science, the enquiry approach aims for a largely tacit understanding. As a result, it is difficult to assess how successful it is, as the outcomes are rather imprecise and difficult to measure. As a method of teaching established scientific knowledge, however, it runs into significant difficulties in practice. These are of three kinds. First, students, because of their inexperience, or the quality of the equipment provided, or the amount of time available, often make observations or measurements which are incomplete, or incorrect, or insufficiently accurate or precise. As a result, the data they collect are not consistent with the intended conclusion. Second, when students do collect data that are good enough for the purpose in hand, they are often unable to draw the intended conclusion from them. The problem lies in the relationship between data and explanation. Ideas and explanations do not simply 'emerge' from data. Rather they are conjectures, thought up imaginatively and creatively to account for the data. It is all too easy for the teacher, or science educator, who already knows the accepted explanations, to underestimate the difficulty of this step. From the point of view of the learner, who does not know the explanation, it is often far from obvious. A third, and more practical, difficulty with the enquiry approach to teaching scientific knowledge is that students know the teacher knows the answer, even if they do not. As a result, they typically look to the teacher to tell them if what they saw as what was 'supposed to happen', and to confirm that their data are 'right' (Driver, 1975; Atkinson and Delamont, 1976; Wellington, 1981).

The issues involved here are essentially epistemological ones. 'Discovery learning' is based on an empiricist view of science and an inductive view of the 'scientific method'. Most mainstream philosophers of science have nowadays moved away from this towards a more hypothetico-deductive view, which recognises the clear distinction between data and explanations. Figure 1 (based on Giere, 1991) summarises this view. By observation and measurement we can collect data on the 'real world'. Alongside this, we may conjecture explanations for the behaviour of this real world. From these, we may be able to deduce some specific predictions – which we can then compare with our data. If these are in agreement, they increase our confidence in the match between the explanation and the real world. If they disagree, they may lead us to question the explanation (or, of course, the specific predictions made from it, or the quality of the data). From an educational point of view, it is the clear separation of data and explanation – and the recognition that there is no direct route from data to explanation – that is the most useful insight.

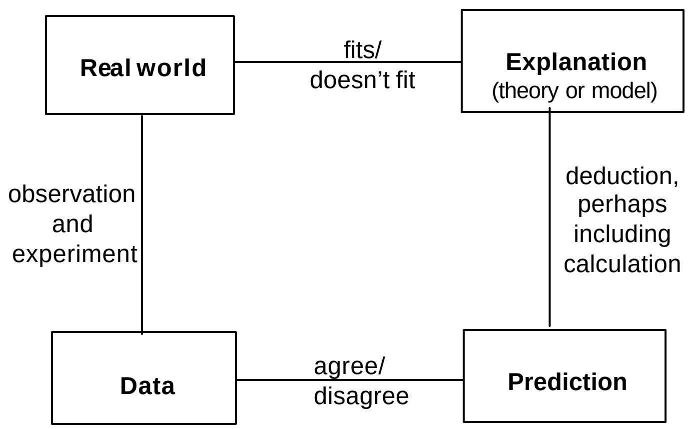

Figure 1 A model of scientific reasoning (based on Giere, 1991)

Although the dominant epistemological view amongst science educators has gradually shifted, over the past four decades, away from an inductive and towards a hypothetico-deductive view, the vision of a form of science education which integrates content and process has persisted. Thompson and Zeuli (1999) argue that such a vision is implicit in the recent standards-based reforms in the USA. This, they suggest[2], sees:

> the classroom as a scientific .. community governed by roughly the same norms of argument and evidence as govern discourse within communities of scholars in the discipline [itself]. Classrooms are scientific .. communities writ small. Science .. education reformers portray effective classrooms as small communities that adopt scientific … modes of communication and other conventions to help them struggle with challenging problems, thus developing systems of shared knowledge that gradually evolve in the direction of the knowledge held by communities of scholars in the discipline. (p. 347)

This does not assume that students will 're-discover' the concepts and ideas of science for themselves, if suitably guided. Rather:

> At key points in the discussion, the teacher may present current scientific accounts of the phenomenon under study, but such presentations should come as answers to questions or solutions to problems that students are actively puzzling over – thinking about – not as answers to questions they have never asked, about phenomena they have never wondered about. (Thompson and Zeuli, 1999: 347-8)

The underlying assumption, as Thompson and Zeuli go on to point out, is that students will gradually construct not only their own understandings of scientific ideas, but will also learn how to carry out for themselves some version of the thinking

[2] I should perhaps make clear that Thompson and Zeuli are not here expressing their own view, but rather summarising the view they think is implicit in other writings and initiatives.

processes that scientists use. Indeed, for some science educators, the aim is that students develop not only 'knowledge-in-action' that enables them to conduct an enquiry 'scientifically', but also explicit, declarative understandings of the nature of science.

In practice, however, there is a significant and quite fundamental tension between the aim of communicating elements of a body of received knowledge and the wish to convey messages about the methods of enquiry used to establish that knowledge in the first place. This can become particularly apparent in the context of practical work. Imagine a school class in which the students are carefully heating a previously weighed sample of magnesium ribbon in a crucible in order to oxidise it. They re-weigh the crucible and contents at the end. Several groups in the class record a weight that is the same as, or less than, the original weight. What is the teacher to do? The same question might be posed about a class in which some students get a negative test result for starch in the leaves of a plant that has been in the light for several days, or where some students record values of electric current that are different at points around a series circuit. In practice, the teacher is likely first to appeal to the norm within the class: what did *most* students find? But if this is not a viable strategy because most did not get the expected result, s/he is likely to engage in a rhetoric of 'explaining away' the observations, perhaps appealing to notions of 'experimental error' or poor equipment. Even if there is time for the teacher to propose that the class should repeat the whole exercise, that is in itself an acknowledgement that what has been observed is not 'what should have happened'. Additional information, not derived from the collected data, is being brought to bear on the situation and used to justify decisions and actions. The alternative – of taking the actual data collected as the warrant for subsequent views and ideas – leads potentially to confusion and is often not viable.

We should not underestimate the depth of the difficulty here. Science is, *inter alia*, a body of established knowledge about the natural world, so teaching science is a goal-directed activity. The aim is not simply to help students develop their understanding of the natural world, but to develop it *in a particular direction* – to bring their ideas and understandings closer to those of the scientific community. Learning science is an induction into a particular view of the world. As a consequence, 'at the school level, … the acquisition of scientific knowledge is inescapably tinged with dogmatism' (Layton, 1973:176; see also Kuhn, 1962, 1963). Many students find this unsettling and even off-putting. Many science teachers and educators are also somewhat uneasy about it. The biology educator Joseph Schwab (1962) castigated it as teaching 'a rhetoric of conclusions'. It does not, however, entail a transmission view of the teaching and learning process. Abstract ideas cannot simply be 'transferred' from teacher to learner; the learner must play an active role in appropriating these ideas and making personal sense of them – and there are no guarantees that the sense that is made is exactly what the teacher intended.

Nonetheless, Layton (1973) concludes that:

> it is difficult to see how both objectives, an understanding of the mature concepts and theories of science and an understanding of the processes by which scientific knowledge grows, can be achieves simultaneously. … The problem of reconciling these objectives in school science teaching has been considerably underestimated. (pp. 176-7)

His view is amply borne out by experience. There are no obvious examples, anywhere in the world, of a form of science education like that sketched by Thompson and Zeuli above being successfully implemented in a national education system. At best, educators may be able to point to isolated instances, where a particularly insightful and gifted teacher has succeeded in sustaining something of this sort for a period of time with some groups of learners. Layton's suggestion that we 'attend to process as a separate objective, important in its own right, alongside content' (Layton, 1973:176) is perhaps a more defensible, and also a more practicable, way of dealing with the tension.

3 The role of practical work in the teaching and learning of science content (scientific knowledge)

3.1 Teaching scientific knowledge as communication

The core problem with the view that students can acquire scientific knowledge through their own scientific enquiry is that it draws erroneous parallels between the teaching laboratory (or classroom) and the research laboratory, and between the purposes (not to say the expertise and confidence) of learners and of scientists. Newman (1982) expresses the difference succinctly when he writes:

> The young child is often thought of as a little scientist exploring the world and discovering the principles of its operation. We often forget that while the scientist is working on the border of human knowledge and is finding out things that nobody yet knows, the child is finding out precisely what everybody already knows. (p. 26)

So learning is not discovery or construction of something new and unknown; rather it is making what others already know your own[3]. The difference is like that between doing the cryptic crossword in today's newspaper, and completing yesterday's crossword using the solution in today's paper, trying to understand how the answers fit the clues.

The teaching of scientific knowledge is essentially an act of communication. Language provides a highly efficient tool for passing on bodies of knowledge and understanding to new generations. For some purposes, however, language alone may not be enough. The central questions about the role of practical work in developing students' scientific knowledge are how, and how effectively, it augments other forms of communication (verbal, graphical, pictorial, symbolic) that teachers might use.

3.2 Why practical experience is essential for understanding the world

Given that the subject matter of science is the material world, it seems natural, and rather obvious, that learning science will involve seeing, handling and manipulating real objects and materials, and that teaching science will involve acts of 'showing' as well as of 'telling'. But what exactly is the role of practical experiences, how do they aid understanding, and are they essential?

[3] Goethe puts this understanding of 'constructivism' rather nicely in *Faust* when he writes: 'Was du ererbt von deinem Vätern hast, Erwirb es, um es zu besitzen.' (Part I, Scene 1, Night, lines 682-3): (What you have inherited from your forebears, make it your own it if you would possess it.)

The central question about knowledge and cognition is: how, exactly, do we (humans) get the world inside our heads? In other words, how do we construct representations of the external world which enable us to live successfully in it, and act successfully upon it when we need or wish to? One influential answer to this is provided by the work of Jean Piaget. Piaget argues that we construct increasingly sophisticated and powerful representations of the world by acting on it in the light of our current understandings, and modifying these in the light of the data this generates. Through action on the world, we generate sensory data which can either be *assimilated* into existing schemas or require that these be changed to *accommodate* the new data, in order to re-establish *equilibrium* between the internal and external realities. Through such action, we construct a view of what objects there are in the world, what they are made of and what can be made from them, what they can do and what can be done to them. If Piaget is correct, then practical experience of observing and (even more important) intervening in the world is essential for understanding.

This account tends to make understanding seem a personal matter – the individual constructing his/her own representations of the world though action on the world. Indeed Piaget's view has been criticised on these grounds. In practice, the representations we construct are tested out not only through action, but also through interpersonal interaction. We talk about how we see things. We bounce our ideas off others, and have them bounce theirs off us. Our ideas are consolidated where they agree with others', and challenged where they differ. Through social interaction, our ideas are modified and refined – so that they are shaped towards a shared set that makes discourse and collaborative action possible.

One word of caution is, however, required. This provides an account of how we acquire commonsense understandings of the natural world, including fundamental ideas such as the very idea of an 'object' itself, of cause and effect, of conservation of number, substance, weight, volume, of classification and groupings and their inter-relations. These basic ideas are regularly tested against experience in everyday situations; they are clearly functional in dealing with these and so are reinforced. Scientific knowledge, however, has been developed for more specific and specialised purposes. Many of its explanations are counter-intuitive and not supported by everyday experience (at least not until you have learned to 'read' that experience in very specific ways). The processes by which they are first arrived at, and by which they are subsequently supported, are more specialised and particular – and depend not only on practical experience but also on culturally mediated interpretations of that experience.

3.3 Practical work involves action and reflection

In the introduction, I defined 'practical work' as any teaching and learning activity which involves at some point the students in observing or manipulating real objects and materials. It is clear from the discussion above, and also widely recognised by science educators, that much of the learning associated with a practical activity takes place through the process of talking about the observations and measurements that have been made, and what they might mean, both with other learners in the class and with the teacher. So a typical practical activity will be followed by a period of discussion of the observations and measurements made, of patterns[4] in them, and of how they might be interpreted and explained. This is so closely linked to the preceding practical activity that it does not make much sense to separate them and regard them as two distinct teaching and learning activities – even if, for practical reasons, the discussion takes place in a subsequent lesson. Instead, we should see the whole activity – the data collection phase and the data interpretation phase – as constituting a practical work task.

The same kind of discussion can, of course, take place in a lesson where there is no data collection because the phenomena which the teacher wants to discuss are ones that s/he can assume are already well-known to pupils from their everyday experience. For example, let's imagine a teacher beginning a lesson on the idea of inertia in Newtonian mechanics. S/he might ask the class if they have ever found themselves having to stand in a bus or train, because it was crowded – and to say what they remember happening (and feeling) as the vehicle started off, or when it braked. From their shared experiences, s/he might then draw out the idea that objects are somewhat resistant to changes in their motion. There has been no practical work in the sense of in-class data collection. But the cognitive processes involved are the same as when data collected by the students are discussed and reviewed. The aim is to draw students' attention to a phenomenon, to isolate parts of it for particular scrutiny, and to talk towards a way of thinking about it. The aim is to develop a link between an observation and a way of thinking about it – between the world and a mental representation of the world. The teacher is, in effect, saying 'see it my way' (Ogborn et al., 1996). We use practical work in science classes when students are unlikely to have observed the phenomenon we are interested in, or to have observed it in sufficient detail, in their everyday lives.

3.4 Two domains of knowledge

The role of practical work, then, in the teaching and learning of science content is to help students make links between two 'domains' of knowledge: the domain of objects and observable properties and events on the one hand, and the domain of ideas on the other (Figure 2) (Millar et al., 2002).

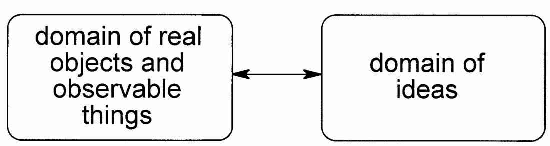

Figure 2 Practical work: linking two domains of knowledge

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[4] By 'patterns', I mean things like similarities, differences, correlations and trends.

How this then plays itself out in practice, and how successful any given practical work task is, depends on the intended learning objectives of the task. Table 1 shows one way of classifying the 'science content' objectives of a practical work task.

To help students to:	
1	identify objects and phenomena and become familiar with them
2	learn a fact (or facts)
3	learn a concept
4	learn a relationship
5	learn a theory/model

Table 1 Possible intended learning outcomes (learning objectives) of a practical work task (science content) (from Millar et al., 2002)

In the first category are practical work tasks whose main aim is to enable students to observe an object or material or event or phenomenon, to note some aspects of it, and perhaps be able later to recall these. This is often a necessary precursor for one or more of the other objectives listed. A 'fact' (objective 2) simply means a 'quickly decidable sentence' (Feyerabend, cited in Maxwell, 1962: 13), in other words an observation statement that can be readily agreed, and is expressed in everyday language, such as that common salt dissolves in water but chalk does not, or that pure water boils at 100^{0}C. A 'relationship' (objective 4) means a correlation or trend – that is, a pattern linking two or more observable properties or characteristics. This might be between observable features of the situation, but could also involve abstractions (for example, modelling situations in terms of variables, relationships involving conceptual terms). Whilst it can be argued that all practical work involves both domains in Figure 2, the domain of ideas is more strongly involved in practical work with learning objectives 3, 4 and 5. For all objectives, but most particularly for objectives 3-5, the qualification implied by the introduction 'to *help* students learn' is important. It is unlikely that a student would grasp a new scientific concept or understand a theory or model as a result of any single practical work task, however well designed. Coming to an understanding of these is more likely to be a gradual process of acquiring deeper and more extended understanding of an abstract idea or set of ideas. Whilst a practical work may contribute usefully to this, it will only be part of a broader teaching strategy.

Many science educators have expressed significant doubts about the effectiveness of practical work for teaching scientific knowledge. Hodson (1991), for example, writes that:

> As practised in many schools, it [practical work] is ill-conceived, confused and unproductive. For many children, what goes on in the laboratory contributes little to their learning of science or to their learning about science and its methods. Nor does it engage them in doi ng science in any meaningful sense. At the root of the problem is the unthinking use of laboratory work. (p. 176)

Woolnough and Allsop (1985) and Osborne (1993), whilst less outspoken, express similar doubts. Section 4 of this paper will look at the role of practical work in relation to students' learning 'about science and its methods'; here the focus is on its contribution to their learning of science. Hodson's criticism has greater force, I think, in relation to learning objectives 3-5 in Table 1. As regards objectives 1 and 2, where the emphasis is more strongly on the domain of objects and observables, practical work has a useful – indeed, I would argue, essential – role to play in science teaching and learning. Students need to observe objects and phenomena in order to have a basis of experience on which to reflect. Without first-hand, practical experience of the world it is hard to see how a student could ever come to an understanding of it. It is hard to imagine, for example, a student who had never seen a chemical reaction coming to an understanding of what the term means from a verbal account, or appreciating what the spectrum of white light looks like without ever having seen what happens when a ray passes through a prism. Practical work is necessary as a component of school science because we cannot assume that students will have observed all the things we want them to have observed in their everyday lives. Even with phenomena which are part of everyday experience, students often have not observed them closely enough to note the features we want them to have noted. For example, many students think that a ball, released from the hand of a person walking along, will fall vertically downwards from the point of release. When asked to observe more closely, most quickly see that in fact it moves in a parabolic curve, with an initial forward velocity equal to that of the carrier.

To what extent, it might be asked, could practical work for these purposes be replaced by non-practical learning activities, such as video-recordings of real objects and events, or computer simulations. As the purpose is to augment students' knowledge of the behaviour of the real world and the objects in it, however, simulations are unhelpful. Video-recordings of events and processes, on the other hand, *can* usefully support learning, by enabling students to view events several times, or to see a wider range of events than would be possible in the school laboratory. But they cannot wholly replace first hand practical experience. The fundamental reason is that the real event contains more information than any representation of it. All representations (video recordings, photographs, diagrams, verbal accounts) are selective, to a greater or lesser extent[5]. They communicate some aspects of the event but not others. A student will get a better 'feel' for what really happens when a piece of magnesium is put into dilute hydrochloric acid, or when two solutions are added and a solid precipitate is formed (to take just two examples), by doing it and observing it, than they could ever obtain from a representation of these processes.

When science educators criticise practical work, it is not really practical tasks with objectives 1 and 2 (in Table 1) that they have in mind. Indeed evidence suggests that these are as effective as many other forms of instruction. Students *do* remember observable aspects of practical tasks, often many months or even years later if the event is a striking one (such as seeing a piece of sodium put into water, or three projected beams of red, green and blue light being overlapped on a screen). Even so, many practical tasks of this type could be made more effective by designing them to animate the students' thinking to a greater extent before they make any observations. One approach which has been found strikingly successful for this is the Predict-Observe-Explain (POE) task structure (White and Gunstone, 1992). In these, students are first asked to predict what they would expect to happen in a given situation and to write this down, then to carry out the task and make some observations, and finally to explain what they have observed (which may or may not be what they predicted). For example, rather than simply recording the speed of a falling object after dropping different distances, students might be asked: 'does a falling object quickly reach a steady speed and then fall at that speed, or does it keeping speeding up during its fall?' Whilst exploring the effect of forces on motion, students might be asked: 'when you kick a ball along the ground, does it continue

[5] In some situations, this selectivity is an advantage, as I will argue later in the case of teaching students about some aspects of scientific enquiry.

to speed up for a while after it leaves contact with your foot?' A teacher with whom I have recently worked stimulated animated discussion in one of her classes by asking students to predict the reading on a top-pan balance when a stone (and, in other similar examples, a wood block, some sand, and some sugar) is moved from a position beside a beaker of water and placed in it (Figure 3) – before going on to check this out by making measurements.

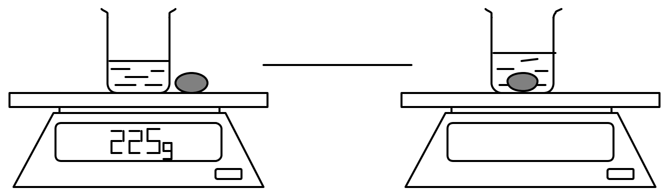

Figure 3 A predict-observe-explain (POE) task on conservation of mass (weight)

Students do have misconceptions about matters of fact – and practical work can challenge these. It does so more effectively if the students' ideas have been declared in advance, and when the practical task can fairly unequivocally endorse one prediction and refute another. The POE structure also makes the practical task more purposeful. Otherwise a practical task designed to enable the students to observe an object or phenomenon can easily become rather dull and uninspiring, unless the event itself is a particularly memorable one.

Where educators' critiques of practical work have greater force is in relation to practical work tasks with objectives 3-5 in Table 1 above. Here both domains of knowledge are strongly involved. The commonest weakness of practical tasks of this sort is taking insufficient account of the need to make links between the two domains. The cognitive challenge for the students is underestimated. Teachers are often blind to the fact that these tasks are cognitively demanding – much more so than those with learning objectives 1 and 2. This is due, in large measure, to the prevalence of the empiricist/inductive view of science discussed in section 2: the belief that ideas will 'emerge' automatically from the event itself, if students work carefully enough. In practice this rarely happens; the hypothetico-deductive view of science can explain why.

Practical work is nonetheless necessary for developing students' understanding of scientific concepts and explanations. It is, as Piaget argued, by acting on the world that our ideas about it develop. Students need to have experiences of acting on the world, in the light of a theory or model, and seeing the outcomes. Only in this way can they come to an understanding of the theoretical representations that we impose on the real world in order to help us explain it and predict its behaviour. For example, when students measure the temperature over a period of time of water in beakers with and without insulating jackets, they are (we intend) coming to see this phenomenon in terms of a theoretical model, of energy moving spontaneously from regions of higher to lower temperature, at a rate which depends on the materials in between. When they measure the electric current at different points in a circuit with parallel branches, they are (we intend) coming to think of current as a flow of something (charge) which is not used up as it goes and behaves predictably at junctions.

Where such tasks fail as learning events, the reason is often that the domain of ideas has been ignored in the task design. Effective practical tasks of this sort have explicit strategies for getting students thinking about the explanatory ideas involved, and not only about the observable phenomenon. Again the POE structure can help, if the students already have enough theoretical understanding of the phenomenon in question to make testable predictions. But other strategies can also be used. Tiberghien (1996), for example, describes a teaching sequence for introducing ideas about energy transfer at secondary school level. This involves presenting students with what she terms the 'seed' of a model, that is, the outline of a way of representing simple processes in energy terms. Students are then asked to look at a number of other energy transfer processes (batteries lighting bulbs and lifting weights, and so on) and to represent these using the same conventions. The fact that students find this quite difficult at first – to a greater extent than many teachers anticipate – is an indication of the cognitive demand. Another strategy is to present and discuss an analogy to which observations and measurements can be directly related. For example, in teaching about the behaviour of simple electric circuits, students might be asked explicitly to relate their observations to a given analogy of circuit behaviour, noting where these agreed with what the analogy would lead you to expect, and where they diverged.

The keys to improving the effectiveness of practical tasks of this sort lies in first helping teachers to appreciate that tasks which require students to make explicit links between the domain of objects and observables and the domain of ideas are challenging, and then to design practical tasks which take this relationship more explicitly and fully into account – and so 'scaffold' students' efforts to make these links. Other non-practical activities, in particular well-designed computer-based teaching materials, including simulations, animations and other kinds of modelling activity, can also be very useful in helping students do the necessary thinking in the domain of ideas[6].

All of this, of course, assumes that the teacher is clear about the intended learning outcome of the practical task. In summary, the characteristics of more effective practical work are:

- the intended learning outcomes are *clear*.
- the task has a *limited number* of intended learning outcomes. It is easy for a practical task to become too complex, so that students get lost in the 'noise' of the bench. If a specific skill is necessary for a task, students need to be competent in this beforehand, or it may get in the way of the intended learning. (For example, if we want students to measure electric current before and after a junction point in a circuit with parallel branches, they must first be competent in building a circuit to match a given diagram, and in using an ammeter to measure current. It is better to establish these competencies in advance than to believe they can be picked up in the course of a more complex activity.).
- if the task requires the students to make links between the domain of objects and observables and the domain of ideas, the structure of the task must 'scaffold' their thinking.

[6] For example, a software tool under development by the Gatsby Science Enhancement Project may be useful for helping students think about simple processes in terms of energy transfers (http://www.sep.org.uk/energy.htm#)

Whilst computer-based instrumentation can enhance some practical activities (for example, by enabling graphs to be generated as the primary data format), it can also add additional layers of opacity and increase the physical and cognitive 'clutter'. Its effectiveness depends on *how* it is used, not *that* it is used. Conversely, many examples of effective practical work use cheap and readily available equipment. Students can be more effectively 'minds on' as well as 'hands on' when they feel they understand how the equipment they are using works.

The discussion above has introduced the term 'effectiveness', so it may be useful to take a step back and ask exactly what this means. We can think of the development and implementation of a practical task in four stages (Figure 4). By 'effectiveness', we usually mean the link labelled (2): do students learn what we intended them to learn? But in order to be effective in this sense, a task must first be effective at level (1), that is, the students must do (and be able to do) the things the task designer intended them to do. A common criticism of practical work in the learning laboratory is that it becomes 'recipe following', with the students often not thinking about *why* they are doing what they are doing. The provision of detailed 'recipes' is a reflection of the teacher's (or task designer's) concern with effectiveness at level (1). Whilst this is a necessary condition for effectiveness at level (2), it is not a sufficient one. As discussed above, explicit design features are often required to help students use their observations to draw the intended conclusions.

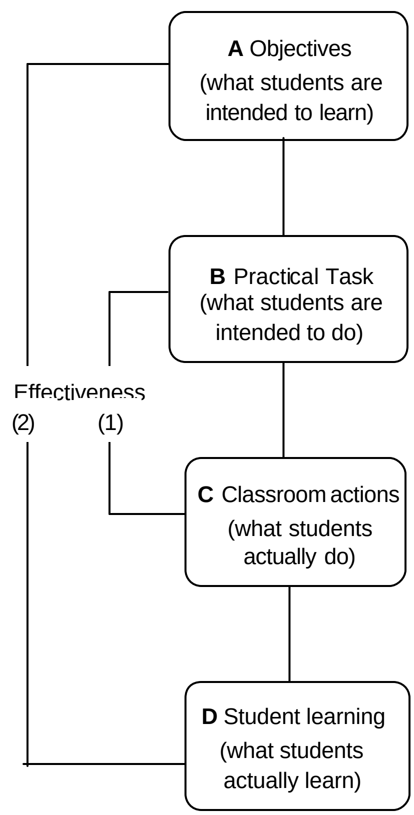

Figure 4 The process of developing and implementing a practical task (from Millar et al., 2002)

4 The role of practical work in teaching and learning *about* science

4.1 Projects and practical investigations

For much of the history of science education, it has been in effect assumed that students will pick up what they need to know *about* science as they acquire scientific knowledge. In that most practising scientists were taught science this way, it seems to be a successful method of developing, in that sub-group, adequate 'knowledge-in-action' of how to 'do science'.

In some science courses and curricula, however, some activities are included with the specific aim of developing students' understanding of scientific enquiry (and their ability to engage in it) and also, perhaps, their ideas about the nature of scientific knowledge. These usually involve practical work of a more investigative, open-ended, project-like sort. Whilst the principal intended learning outcome is practical capability (the ability to plan, design and carry out a scientific investigation), they may also, to a greater or lesser extent, seek to develop students' declarative knowledge of the nature of science.

There is evidence that experience of carrying out extended practical projects can provide students with valuable insights into scientific practice and can increase interest in science and motivation to continue its study (Jakeways, 1986; Woolnough, 1994). Examples of the successful use of extended projects are, however, mainly at upper secondary school level or above, where students are to some extent self-selected, teachers have (in general) better subject knowledge, and groups sizes are smaller. There are few examples of the successful implementation of extended practical projects or investigations as part of the science curriculum in the context of 'mass education', where large numbers of teachers and students are involved. Teachers find it difficult to devise or to help students to generate enough project ideas, year on year. It is easy for the activity to become routinised, and become something very different from what was originally envisaged when it was included in the curriculum.

This is very much the story of Attainment Target 1 'Scientific enquiry' in the English national curriculum (DfEE/QCA, 1999). This lists some specific points that students should be taught, under the general heading of 'investigative skills'. These are at a very general level, for example, that students 'should be taught to use observations, measurements and other data to draw conclusions' (p. 29). The way in which these are then interpreted and operationalised for the purposes of national examinations at age 16, however, has resulted in many teachers using the same small set of practical tasks from year to year, chosen to make it as easy as possible for their students to include those features for which the teacher can award marks. Without being explicitly told what to do, students are then coached and corralled through these activities so that they obtain as high marks as possible [7]. Also, the assessed investigations become almost the only investigations actually done. (For a fuller account of the rather dismal history of this curricular experiment, see Donnelly et al., 1996).

[7] The fact that schools' average scores are published nationally in the form of 'league tables' of school performance is a strong influence on these practices.

When investigative practical work is included in the science curriculum, it is also often criticised for portraying an inaccurate or incomplete image of scientific enquiry. In particular, the kinds of tasks which students undertake are often empirical investigations of relationships between variables. Whilst this is one important form of scientific enquiry, and highlights some important ideas about scientific (and logical) reasoning, focusing on it to the exclusion of other aspects of the scientific approach leads to distortion. The basic flaw in this image of scientific enquiry:

> is the apparent assumption that science is a sort of commonsensical activity. … There seems to be no explicit recognition of the powerful role of the conceptual frames of reference within which scientists and children operate and to which they are firmly bound. (Atkin, 1968: 9)

This criticism has also been levelled at the English national curriculum, which has sought to address it in its most recent revision (DfEE/QCA, 1999) by adding a strand, and some teaching targets, on 'ideas and evidence in science'. It is too early to say with any certainty what impact this will have on practice. Overall, however, the introduction of investigative practical work in the English national curriculum has led to rather disappointing practices. In part, the problems can be traced to lack of clarity about the intended learning outcomes. The inclusion of investigative practical work stems from a rather broad and general, and somewhat romantic, view of its educational benefits. Doing a practical project is seen as 'a good thing'. It is also seen as a means of escaping from 'recipe following', or 'cookbook', practical work. This is a laudable enough aim; following instructions, without thinking about what you are doing or why, is unlikely to lead to learning. Students who have been involved in deciding some of the features of the practical task they are engaged in (the question it addresses, the apparatus and equipment they will use, the data they will collect, how they will analyse and interpret these) are more likely to think about what they are doing and finding, and to learn from it. But without more specific targeting of learning outcomes, students often show disappointingly little improvement with age and experience in their performance of practical investigations.

One final word of caution about practical projects and investigations. It is important (yet again) to recognise the differences between the teaching laboratory and the research laboratory. Research scientists explore the unknown, seeking to add to public knowledge. They are committed to extending the boundaries of the known, and believe they are capable of doing so. Student investigations in the teaching laboratory are either of phenomena whose interpretation is well established and beyond serious question, or of local or particular phenomena of little wider, or theoretical, significance or interest. The tasks in which they are engaged are not, whatever some science educators' rhetoric might imply, 'authentic', if by that we mean that they are closely similar to those undertaken by professional scientists.

We would do better to recognise that *all* practical tasks in the teaching laboratory are simulations, that is, they model some aspects of professional scientific practice and not others. This can be a benefit as well as a constraint. We can choose the aspects we wish to model, provided we are clear enough about our intended learning objectives. The next section will look briefly at what that might entail.

4.2 Teaching the nature of science

The arguments for including knowledge of the nature of science as a curriculum objective would seem to require actions that go beyond attempting to develop students' ability to undertake more open-ended practical investigations. At the very least, they would seem to require some reflection on the investigative process itself, and on the nature of the knowledge produced, both in the students' own investigations and also in the work of professional scientists. The latter seems essential if issues of theory development and theory change are to be considered.

To make progress we need to probe more deeply into what is meant by 'an understanding of the nature of science' and try to make clear exactly what we would like students to understand. Whilst consensus about the nature of science is considerably weaker than about scientific knowledge itself, there is a core of ideas to which most would subscribe. These might be summarised as follows:

- all scientific knowledge is systematically informed by observational data;
- for data to become evidence, they must be interpreted within theoretical and practical traditions;
- interpretation is an open-ended and flexible process, so interpretations may legitimately differ, and the outcome is always essentially provisional.

Unpacking this a little might then lead to the following learning objectives:

- an appreciation that all observation and measurement is inevitably subject to uncertainty (in other words, you can never be sure that you have made a 'true' observation or measurement) – and a knowledge of how to judge the extent of this and how to deal with it;
- the ability to model simple phenomena in terms of the effect of one or more independent variables on a dependent variable (and associated ideas about control of variables and 'experimental design' more generally);
- an understanding of the relationship between data and explanation, along the lines of Figure 1 above (in particular, an awareness that explanation is distinct from data, and cannot be simply deduced from it);
- some understanding of the role of the scientific community as a 'quality control' mechanism and of its 'institutional norms' (universalism, communalism, disinterestedness and organised scepticism) (Merton, 1942).

Practical work has an important role to play in this – alongside other teaching approaches. More specifically, practical work is essential for giving students a 'feel' for the problematics of measurement, and an appreciation of the ever-presence of uncertainty (or measurement error). It is also an important tool for teaching about experimental design. Indeed research suggests that students design better investigations when they actually carry them out than when only asked to write a plan; feedback from experience improves design (APU, 1988: 100).

Practical work of this sort can, however, be made much more effective that it often is at present by more careful and detailed task design, starting from greater clarity about the intended learning outcomes. If we want to highlight the problem of measurement uncertainty, and begin to explore ways of estimating it and dealing with it, then practical tasks need to be designed to focus students' attention on the key ideas. As with teaching science content, the task will only work if it triggers acting thinking on the students' part. So, for example, tasks which ask students which of two given objects or materials is heavier, denser, of higher resistance, or whatever, can stimulate much debate and argument, especially if examples are chosen that progressively challenge the limits of accuracy of the available measuring equipment. Similarly, students can learn important ideas about data interpretation from practical tasks that ask them to find out whether a given independent variable does or does not affect a dependent one (for example, does the mass on the end of a pendulum affect its time of swing?) Compared to showing that two variables co-vary, collecting good evidence that one variable has no effect on another is a considerable challenge (Kanari and Millar, in press), which can both reveal and help to develop student's ideas about data collection and interpretation. Unless tasks are designed with specific, and progressively challenging, objectives in mind, the evidence suggests that students' thinking about scientific enquiry advances little if at all. Many children by age 9 appear to grasp the idea of a 'fair test' – the need to vary only one thing at a time in order to find out how a specific factor affects the outcome – in the context of comparisons of cases. This does not, however, appear to develop smoothly into the ability to design well-planned investigations of the effect of two continuous variables, which many cannot manage confidently by age 16. A clearer and more detailed analysis by science educators of this knowledge domain is a necessary first step, to identify pathways along which students' understandings might be developed.

For teaching all these ideas about scientific enquiry, and in particular for teaching about the relationship of data and explanation and the role of the scientific community, non-practical methods are also necessary. In the UK, the widely adopted teaching materials of the Cognitive Acceleration through Science Education (CASE) project (Adey et al., 1995) include explicit teaching of ideas about variables, control of variables and experimental design. Teachers using these see them as stimulating change in students' ideas and understandings. Computer-based simulations may also help to reduce the 'noise' of the laboratory bench and focus attention on important aspects of experimental planning and data interpretation (Millar, 1999). Data interpretation tasks, including exercises like those used by researchers (for example, Kuhn et al., 1988; Koslowski, 1996), may also be useful in probing and developing students' ideas about the relationships between data and explanation. Historical material on the emergence of consensus about some important scientific ideas and explanations may be needed to explore warrants for knowledge, and the role of the scientific community in establishing ideas as 'knowledge'. Computer-based tools (for example, Bell and Linn, 2000; Sandoval, 2003) may be of considerable value in engaging students more actively in thinking about issues of theory choice.

There is a tendency, linked to the ascendancy amongst science educators of the 'critical perspective' on scientific literacy rather than the 'enlightenment perspective' (Irwin, 1995), to emphasise the provisional and revisable character of scientific knowledge. Yet the characteristic of science – the thing that makes it really distinctive – is not that it produces contested knowledge of the world. Many forms of intellectual activity can do that. What is distinctive about science is that it has, as a matter of fact, produced a few little islands of consensus – areas of knowledge where it no longer seems worthwhile disputing the accepted interpretation. Do any of us really believe that we can only claim that infectious diseases may be transmitted by micro-organisms, or question that water really is H_2O, or that the shape of a DNA molecule is a double helix? Within the discussion of epistemological ideas, it may be important for students to have the opportunity to consider in some depth a few examples of the process of arriving at consensus, of the closure of debates. It would clearly not be possible to do this for all of the science content we might wish to teach, but it may be valuable to do it for a few topics. Whilst this is unlikely to involve a great deal of practical work, it might provide the intellectual resources to resolve (or at least diminish) the tension discussed at length above, between the messages implicit in practical work to support the teaching of scientific knowledge and the explicit ones we might wish to communicate about the nature of science.

Finally, to conclude this section, it may be important to note that, in courses whose purpose is to enhance students' scientific literacy (as distinct from the pre-professional training of scientists), practical work is a means to an end, and not an end in itself. Citizens do not (*qua* citizen) undertake scientific enquiry (some may engage occasionally in systematic enquiry – which is not the same thing). So they do not require to become proficient in it. They are *consumers* of scientific knowledge, not *producers* of it. To become more intelligent consumers, they may benefit from some experiences of practical work, but the aims need to centre on developing the knowledge and understandings required to respond intelligently to scientific information as it is encountered in out-of-school contexts.

5 Summary

It may be useful to end this paper by summarising briefly its main points about the role of practical work in science teaching and learning.

1. Practical work is an essential component of science teaching and learning, both for the aim of developing students' scientific knowledge and that of developing students' knowledge *about* science.

2. In thinking about the role of practical work, it is important to bear in mind the significant differences between the research laboratory and the teaching laboratory (or classroom); and between research scientists exploring the boundaries of the known and students trying to come to terms with already accepted knowledge.

3. In the context of teaching scientific knowledge, practical work is best seen as *communication*, and not as *discovery*.

4. Practical work to develop students' scientific knowledge often requires students to make links between two domains of knowledge; that of objects and observables, and that of ideas. Where the aim is to help students learn a concept, relationship, theory or model, the task design needs to 'scaffold' students' efforts to make these links.

5. Practical work to develop students' scientific knowledge is likely to be most effective when:
   - the learning objectives are clear, and relatively few in number for any given task;
   - the task design highlights the main objectives and keeps 'noise' to the minimum;
   - a strategy is used to stimulate the students' thinking beforehand, so that the practical task is answering a question the student is already thinking about.

6. Practical work of a more open-ended, investigative kind can develop students' tacit knowledge of scientific enquiry. Attempts to include this in the mainstream curriculum, however, are liable to result in practice that is disappointingly different from that intended, especially if students' performance of investigative tasks forms part of the course assessment.

7. Targeted practical tasks can be very useful for developing specific understandings about data, experimental planning, and data interpretation. Like those aiming to teach scientific knowledge, effectiveness starts from clear, and limited objectives. The other criteria identified in point 5 above again apply.

8. For some of the understandings *about* science that we might wish to develop, methods other than practical work are also likely to be required.

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