Teaching and learning science through practical work

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Practical work in science teaching

Practical work is a very prominent feature of school science in many countries. A high proportion of lesson time is given to practical work, usually carried out by pupils working together in small groups. In countries where this is not the norm, increasing the amount of practical work is seen as progress

However, where practical work is widely used, many educators express concern that it is not effective in promoting learning. As anyone who has taught science knows, students often fail to learn from practical work the things we intend them to learn. Frequently practical work is carried out very rapidly, or with unreliable equipment, or with little time to practice the use of the equipment before making measurements – and these are often taken with insufficient attention to care and precision. As a result students may fail even to produce the phenomenon they are supposed to observe, let alone be helped to appreciate patterns, trends or explanations. Even when they do make the measurements or observations the teacher intended, conclusions which seem 'obvious' to the teacher can appear less so to the student. Often practical work is humdrum and routine, rather than engaging or inspiring. In a strong critique of current practices, Hodson (1991) writes:

> As practised in many schools, [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 doing science in any meaningful sense. At the root of the problem is the unthinking use of laboratory work. (p. 176)

These concerns have led to calls for more 'authentic' practical experiences, or to re-think, re-evaluate, and perhaps reduce, the amount of practical work, to leave more room for other kinds of learning activity

Some teachers who are aware of these debates and discussions ask: is practical work effective? Is it a good way to teach science? In my view, practical work is an essential – indeed inevitable – aspect of teaching science – because of the subject matter of science. The aim of science is to gain an understanding of the material world – to be able to explain events and phenomena, and perhaps become able to control some of them in some ways. Indeed, we value science because it has been successful in this. The aim of science education is to pass on to young people some elements of this knowledge and understanding that we (as a society) feel are of value to them. Because science education is about trying to pass on knowledge and understanding about the physical world, it is natural that this will involve acts of 'showing' as well as 'telling'.

We just have to think of how difficult it would be to communicate to someone who had never seen it what the interference pattern produced by light passing through two slits, or the refraction of a ray of light passing through a glass block, actually looks like. It is much easier and more effective to show it than to describe it in words. Words only convey part of the information present in the actual event.

So the important question is not whether we should use practical work in science education, but how we can use it well. How can we design practical work so that it is effective? Two things need to be said straight away about that question. First, 'practical work' is a very broad category. So it doesn't make much sense to ask if 'practical work' is effective. Different pieces of practical work have different learning aims. We need instead to ask two questions about each specific example of practical work:

- what is this piece of practical work for?
- is it effective in reaching these aims?

And we also need to clarify what we mean by 'effective'. To do this, it is useful to consider the whole process of devising a teaching and learning activity, and the various influences on it at different stages. Figure 1 shows a possible model of this.

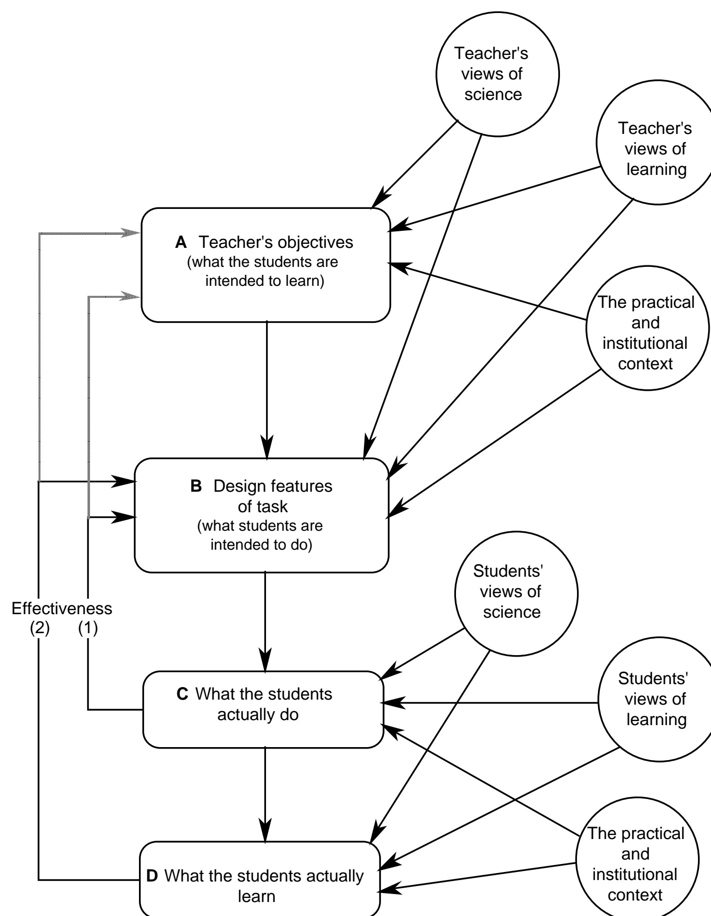


Figure 1. A model of the development of a teaching and learning activity

The most basic level of effectiveness is to do with whether the students in fact do the things we intend them to do as they carry out the practical task. In Figure 1 this is called ‘effectiveness 1’. If they do, we can then ask the further question: do the students learn from the task the things we intend them to learn? This we might call ‘effectiveness 2’. If they do not, we might then want to revise the task, or even rethink the learning objectives. Any assessment of effectiveness 2 depends, of course, on first having identified clearly the learning objectives of the practical task. This is a rather obvious requirement: if you don’t know exactly what you’re trying to do, then you have no way of judging how effectively you’re doing it.

Learning objectives for practical work

In one recent project I was involved in, we developed the coding scheme shown in Appendix 1 to help identify the main learning objectives of some examples of practical work. A group of teachers independently used this coding scheme to classify a set of 12 examples of practical work.

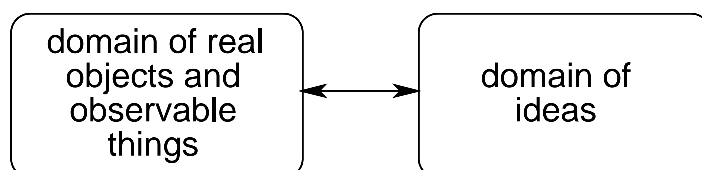
The main outcomes of this exercise were:

- the teachers reported that they found it a valuable exercise in helping them to think harder about the objectives of practical work
- this coding scheme seems to include most examples of practical work that are used in schools
- in general, teachers were consistent in coding tasks into the major categories (content, process, etc.)
- <u>but</u> they did not agree closely in their detailed coding within the code groups 101-103, and 108-110.

It may therefore be worth looking in more detail at these two areas: practical work which aims to teach some science content, and practical work which aims to teach some aspect of scientific method.

Practical work to teach science content

The fundamental purpose of practical work is to help pupils make links between two domains of knowledge.



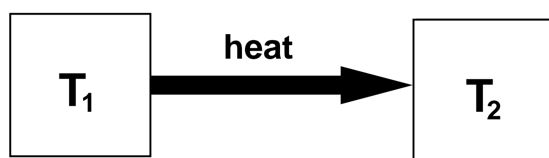
In some practical tasks, the emphasis is more strongly on the domain of real objects and observables. The aim of the practical work is to help pupils to notice a phenomenon, perhaps to look at it in more detail than before, and perhaps to remember it afterwards. Some practicals have an aim which is closely related to this, namely to help pupils refine their use of terms (such as *dissolving*) or to learn a new

term by seeing some examples of it (such as *refraction, interference pattern, gas evolved in a reaction*).

In other practical tasks, however, the real learning challenge is to make links between the two domains – relating what you see to ideas you might have about it. Tasks like these need to be designed carefully. To evaluate them, we need to explore how successful pupils are in making links between the two domains.

One example of this kind of research evaluation comes from my own work with a doctoral student, Mike Arnold (Arnold and Millar, 1996). We looked at pupils' learning of the basic scientific model of thermal processes. This, when you start to think about it in detail, is not as simple as it might at first seem. Figure 2 summarises the main ideas in the scientific model. In addition to these, the pupils need to appreciate that one of the 'objects' in the situation might be the environment, which can act as either a source of heat, or a sink for heat.

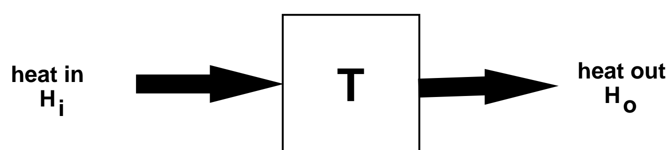
a.



If T1 > T2, heat flows in the direction shown.

For any given pair of objects, the bigger (T1 - T2), the greater the rate of heat flow.

b.



If Hi > Ho, T rises.

If Hi < Ho, T falls.

Figure 2. The basic scientific model of thermal processes

In our teaching, we began by asking some 13-14 year old pupils to do a simple practical task which involved heating some water in a tin can using a candle (Figure 3). Pupils were asked to measure the temperature each minute for 15 minutes, and explain what they observed. In fact the temperature rose steadily at first, then levelled off at around 50°C (the exact temperature depends on the volume of water used and the distance between the flame and the can).

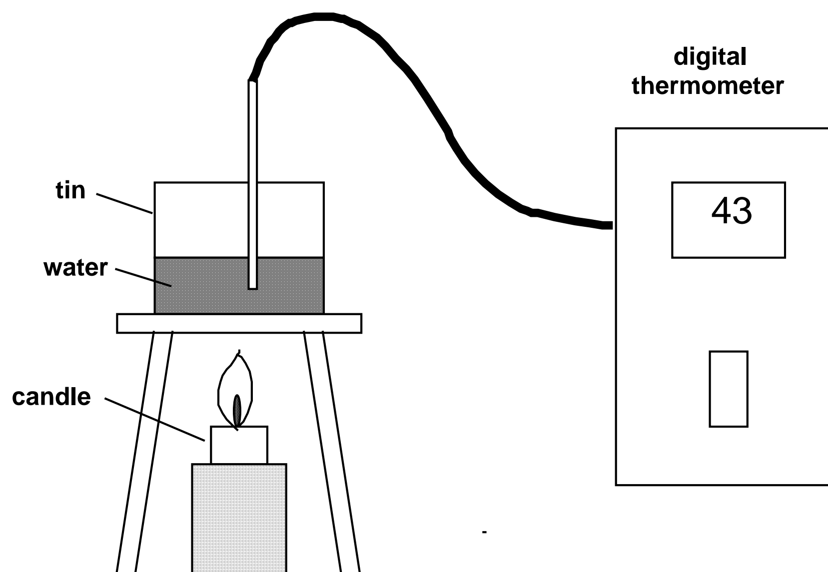


Figure 3 The water heating practical

None were able to explain this using the scientific model as these sample explanations show:

> Eventually the heat is enough...the candle can't give more.
>
> ...I think there must be an optimum ... because the heat of the power source is limited ... I would expect it to reach an optimum point
>
> No ... is it that the heat stops the same but actually it's heating less water ... as time passes on ... so the heat's more intense?
>
> ... the water is as hot as the candle and the candle can't get hotter so can't rise the temperature any higher than its own.
>
> ... the water's at its boiling point and so it can't go any hotter.

So we then introduced the pupils to an analogy: water flowing in and out of a glass beaker. We asked them what would happen to the water level if water was flowing in at a faster rate than it was flowing out – and what would happen if the outflow was faster than the inflow. And we discussed what would keep the water level steady. Most of the pupils understood this quite easily. We then helped them, through discussion, to see the parallels between this and the heating situation. (It is necessary

to help pupils see these links; most do not see them easily for themselves.) After this, and some other practical work involving things heating up and cooling down, about half of the group were able to use the analogy to help explain the heating situation, as these answers show:

> We kept the water at the same level by controlling the input and the output of water and making it the same (the water coming into the jar the same as the water coming out of the jar).
>
> The temperature stayed at the same level because the amount of heat input was the same as the amount of heat output (heat going into the jar the same as the heat going out of the jar).

> We put the same amount of water in as the same we let out.
>
> The temperature kept at the same level because the heat from the candle that went into the tin came back out from the top of the tin in the same amount.

Another example of this kind of study of how students make links between what they observe and the ideas we use to explain it comes from Andrée Tiberghien's work on teaching energy (Tiberghien, 1996). She uses what she calls a 'seed' of theory to start things off. Students are given a battery and bulb, plus a diagram showing the event in energy terms (Figure 4). They are then asked to represent some other energy change events using the same kind of flow diagram. Many students cannot at first do this, and most take some time to work out the links between the abstract representation and the actual objects and events they are observing.

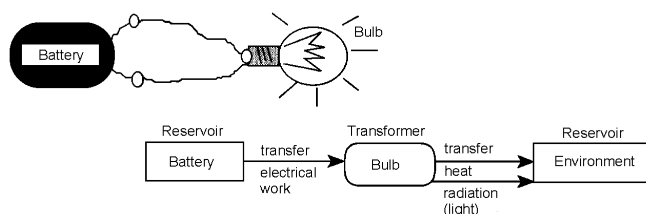


Figure 4 A 'seed' of theory which students then try to apply to other situations (from Tiberghien, 1996)

Another rather different way of asking students to link the two domains of objects and ideas is through Predict-Observe-Explain (POE) tasks (White and Gunstone, 1992). These can be very useful, for instance, for consolidating and developing students' understanding of electric circuits, by asking them to predict what will happen in a given situation, then to do it and, if their prediction was wrong, to explain what they now observe.

To conclude this section, there is one point that I think is very important to make about practical work that is intended to support the teaching and learning of scientific

knowledge. This kind of practical work is best understood, and should be evaluated, as a communication strategy - as a means of augmenting what can be achieved by word, picture and gesture. It should not be criticised for being different from what 'real scientists' do in the research laboratory. It has an entirely different function. Exploring the unknown is not the same as communicating the known. Newman (1982) makes this point very succinctly:

> 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)

For this reason, practical work that is intended to teach science content does not have to be 'authentic', or similar to our idea of what 'real' science is like. This is not an appropriate criterion for judging a practical task. Indeed there are good reasons why it cannot be similar to 'real' research science. Instead, a good practical task for teaching science content is one which communicates effectively the ideas it sets out to communicate.

Practical work to teach some aspect of scientific method

Let me turn then to the second main category of science practical tasks – those which aim to teach students something about scientific method. In the small study I mentioned earlier, the group of teachers had some difficulty in discriminating between the different learning objectives listed within this group – they tended to code each task with <u>all</u> the codes in the group. The underlying difficulty here, I think, is that we are not as clear as we need to be about what exactly we mean by 'scientific method'. It is easier to talk about teaching 'scientific method' than to say exactly what it is.

Rather than try to define it, let me suggest an operational definition. A person could be said to understand the scientific method if they can:

- propose questions about the physical world that could be investigated scientifically
- devise a sensible plan for collecting data to answer such a question
- use data they have collected to make a sound argument to support their conclusion.

To teach this, we will need to use tasks in which the pupils have some control of the decision-making process, and do not simply have to follow a 'recipe'. If we consider the aspects of a practical task listed in Table 1, then a task to teach about scientific method will need to have several ticks in the right hand, or middle column.

Aspect of labwork task	specified by teacher	decided by student-teacher discussion	chosen by students
Question to be addressed			
Equipment to be used			
Procedure to be followed			
Methods of handling data collected			
Interpretation of results			

Table 1 Assessing the open-ness of a practical task

However, we then come up against a dilemma. If we allow pupils to choose the questions they investigate, this gives them maximum 'ownership' of the task and may make it more motivating, as pupils really understand the purpose of what they are doing. But, there is a price to pay: pupils often choose a task that is rather too easy for them, and so they learn little from it. On the other hand, if the question to be answered (though not the method for tackling it) is given by teacher, the students may have less interest in the task, and may not have as clear an understanding of its purpose. But the teacher can plan a sequence of enquiry tasks to develop and extend the pupils' understanding. My own view is that we need to use the structure provided by the second approach, whilst trying to involve the students as much as possible in devising tasks, and doing all we can to make these interesting and meaningful to the students.

Whichever approach we favour, the fundamental aim is that pupils should improve their understanding of the scientific method. This, of course, requires that we have a model of what this learning involves, and of how students' understanding should progress. I do not know of any detailed models of this at present in the science education literature. So we need to start trying to build one. This is too big a job to do in this paper, but we might look at some of the features that such a model would need to have. A useful starting point is to separate out three 'levels' of information and reasoning:

Data	(PHENOMENON-BASED reasoning)
Patterns, relationships and trends	(RELATION-BASED reasoning)
Explanations ('stories')	(MODEL-BASED reasoning)

We can then ask what we would like pupils to understand at each of these levels. The ideas that follow are taken from a Report prepared for the Qualifications and Curriculum Authority in England to inform their thinking about the future development of the science curriculum (Millar et al., 2001).

At the level of *Data*, we might want pupils to understand that:

a. Data is very important in science. We build our understanding on observations, and test our ideas against observation. We cannot just think whatever we like; it has to be consistent with the data.
b. No measurement is ever absolutely exact, either because the property being measured keeps varying, or is not precisely defined, or because the measuring equipment is not perfect.

c. We can often get a better estimate of the 'true' value by taking several measurements of the same thing, and averaging these.
d. It is better practice to state a measurement as a range, within which the 'true' value probably lies, than as a single figure. (The range can be estimated from the largest and smallest measurement in a set of repeats, or by judging the accuracy possible with the measuring instrument.)
e. If a few measurements in a set of repeats are very different from the rest, it is sensible to check these and reasonable to omit them from the data set.

The level of *Patterns* includes things like differences and similarities, correlations, causal links, and relationships between variables. At this level, we might want pupils to understand that:

a. It is reasonable to conclude that two quantities are <u>really</u> different if their difference is greater than the (observed or estimated) variation in repeat measurements of them.
b. When investigating something, scientists often look for a link (a correlation) between a factor that can be present or absent, or can change in value, and an outcome.
c. A correlation between a factor and an outcome does not necessarily mean that one of them causes the other; both of them might, for example, be caused by some other factor.
d. In order to investigate the relationship between a factor and an outcome, we have to think of all the other factors which might affect the outcome and, if we can, keep them constant.
e. When investigating the effect of a factor that can vary in value, the relationship can be seen more easily, and explored in more detail, if the measurements are displayed as a graph. This can help us to predict what a new measurement will be without actually having to making it (or <u>before</u> making it if we want to check our ideas).
f. If a few measurements do not fit the pattern shown by the majority, then it is often sensible to check these and reasonable to omit them from the data set.

Finally, at the *Explanations* level, we might want pupils to understand that:

a. An explanation doesn't just 'emerge' from the data, but has to be thought up imaginatively to account for the data.
b. Some scientific explanations are based on models which propose the existence of things that cannot be directly observed (e.g. the particle model of matter, the gene model of inheritance), or a new way of looking at a situation (e.g. the heliocentric model of the solar system, the plate tectonic model, the theory of evolution by natural selection).
c. An explanation should account for things that have been observed. Some very powerful scientific explanations account for a lot of different things that otherwise seem to be completely unrelated. Ideally an explanation should lead to some new predictions. It should also be consistent with other accepted explanations.
d. Scientific explanations are tested by seeing if predictions based on them match with observation. (This is what an 'experiment' is.)

e. A good match between observation and prediction increases our confidence in an explanation, but does not prove it is right.
f. A mismatch between observation and prediction casts doubt on an explanation but does not prove that it is wrong. (It is possible that the observation is inaccurate, or the reasoning leading to the prediction is wrong.)

One tool to help pupils make progress in their understanding of scientific method is to encourage them to put forward, and to investigate, increasingly precise and detailed hypotheses, by moving up the following levels:

Level 1: *descriptive hypotheses* (X is bigger, stronger, etc. than Y.) (Tasks like these might be thought of as technological, rather than scientific.)

Level 2: *predictive hypotheses* (As X gets bigger, Y will get bigger.)

Level 3: *contextual hypotheses* (As X gets bigger, Y will get bigger, because of Z.)

So, to summarise, in this area of science teaching and learning, I think we need to recognise that:

- There is a content to teach (we might call it 'procedural knowledge', or perhaps more accurately 'knowledge of accepted scientific procedures').

- Teaching and learning tasks need to be carefully designed, so that the key teaching point is communicated clearly (or has a reasonable chance of emerging).

- The sequence of practical tasks is important. They need to progress towards more demanding ideas.

- Pupils' science content knowledge does interact with their knowledge of accepted scientific procedures (as reflected in their performance of practical investigations). Pupils do better on tasks where they feel they understand the ideas involved. So it may be sensible to develop understanding initially in domains with a relatively low conceptual demand.

The priority task for research in this area is to deepen our understanding of the specific ways in which pupils' ability to perform science investigation tasks improves with experience, or as a result of teaching. From this we then need to develop a detailed, research-based model of progression in understanding of scientific procedures. I hope that the ideas sketched out above might help us to make a start on that task.

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Appendix 1: Coding scheme for the main intended learning outcomes (or objectives) of a practical task

Outcomes relating to **scientific knowledge**

As a result of doing this practical task, the pupils are expected to learn….

Code		
101	**.. a fact (or facts) about the natural world**	By a 'fact' we mean something directly observable, that they would be expected to recall later. It might be something new - or a reminder of something they may have met before.
102	**.. about a pattern or relationship**	By a 'pattern' or 'relationship', we mean things like: that metals are good conductors of heat; that when X gets bigger, Y gets bigger; that mass in conserved in a change of state, etc.
103	**.. (or to improve their understanding of) a science concept or theory**	It is probably unrealistic to expect a pupil to 'learn' a science concept from one practical task, hence the addition of the words 'or to improve their understanding of ..'
104	**.. how a piece of scientific knowledge is applied**	For example, in a device, or to account for an everyday phenomenon.
105	**.. something about how science is applied in industry**	

Outcomes relating to **practical capability**

As a result of doing this practical task, the pupils are expected to learn….

106	**.. how to use a piece of laboratory apparatus, or carry out a standard laboratory procedure**	For example, they may have learned, or practised, how to use a measuring instrument, or how to set up and use a piece of standard laboratory equipment, how to carry out a standard procedure (so that they could do this again on a future occasion).
107	**.. the skill required to carry out a task requiring careful or precise manipulation**	i.e., they will have developed their ability to manipulate a piece of equipment to obtain a reasonable result, where this requires some manipulative skill (rather than just knowing what to do).

Outcomes relating to **capability in scientific enquiry**

Note: All the codes in this group begin with the words 'learn something about', because it is unlikely that the pupils would be expected to learn all there is to know about this from one practical task. Note, too, that many practical tasks require pupils to do these things, but that does not mean that they are necessarily the main learning objectives of the task. Choose one of these codes only if you think one (or more) of these is a **main learning objective** of the task.

As a result of doing this practical task, the pupils are expected to learn….

108	**.. something about how to plan a good investigation**	For example, knowing what to change, what to keep the same, what to measure; designing a 'fair test' where this is relevant; deciding how many measurements to make, etc.
109	**.. something about how to make hypotheses and predictions**	
110	**.. something about how to make accurate and detailed observations**	
111	**.. something about how to follow instructions accurately**	

Outcomes relating to **communication in science**

Note: Again all the codes in this group begin with the words 'learn something about', because it is unlikely that the pupils would be expected to learn all there is to know about this from one practical task. Note, too, that many practical tasks require pupils to do these things, but that does not mean that they are necessarily the main learning objectives of the task. Choose one of these codes only if you think one (or more) of these is a **main learning objective** of the task.

As a result of doing this practical task, the pupils are expected to learn….

112	**.. something about how to analyse and present data**
113	**.. something about how to draw conclusions from data.**
114	**.. something about how to evaluate the quality of data**
115	**.. something about how to present an account of a practical task**

Outcomes relating to **personal development**

As a result of doing this practical task, the pupils are expected to ….

116	**.. be more motivated to study science**
117	**.. be more confident and self-reliant**
118	**.. have learned something about how to work effectively with others in a group**