The role of 'practical' work in teaching and learning chemistry

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ABSTRACT This article sets out to consider what we might mean by 'practical' work, and the different purposes we might have for laboratory activities, in teaching chemistry. One common aim for student practical work is to support the learning of chemical concepts, but both the nature of chemical ideas and the demands of undertaking laboratory work can act as barriers to effective learning. The article analyses one common chemistry practical to illustrate why learning from student laboratory work can be challenging for students. Suggestions are offered for the effective use of chemistry practical work.

One common theme that is elicited when adults are asked about their recollections of school science is the 'bangs and smells' they remember from school chemistry. It seems that being scared by an unexpected bang, or revolted by an unpleasant smell, often leads to a treasured school memory. It is also the common experience of science teachers that most students seem to enjoy the practical side of chemistry lessons – the mixing of solutions and working with beakers and test tubes that perhaps seems to offer a taste of 'being a scientist'. Students beginning secondary school have been reported to note that they are doing 'proper' science – because they now get to use Bunsen burners. Experienced science teachers are likely to recognise the regular request of 'can we do practical work today?', and perhaps also the potential potency of the threat that a practical activity will be curtailed unless some particular behavioural issue is quickly addressed.

Despite this, it is less clear that school laboratory work is the major contributor to learning science that student enthusiasm might imply, or teacher commitment to the sciences as 'practical subjects' would suggest. In the UK tradition, teachers and students generally consider practical work a key aspect of learning science: yet the evidence suggests that the time and resources given to laboratory work can pay limited dividends in terms of learning of, or attitude to, science (Abrahams, 2011). This is important across the sciences but has particular resonance for chemistry teachers both because the subject can involve high expenditure on consumables (materials, replacing broken glassware) and because the health and safety concerns associated with some chemicals can make risk assessment a challenging business.

Teaching chemistry also has the added challenge that the phenomena of chemistry are often not obviously related to the theoretical models used in the subject, given that so much of modern chemical theory relates to the molecular level. Biology and physics also develop theoretical ideas about scales beyond immediate observation (we cannot see photosynthesis occurring, or go back to the conjectured 'Big Bang'), but in those subjects it is often possible to defer teaching about these models of the 'invisible' until the later secondary years – whereas an appreciation of the molecular realm is fundamentally linked to an understanding of chemistry at a theoretical level.

Active learning, practical work and laboratory work

It is useful to clarify how 'practical' work links to terms such as laboratory work, active learning and enquiry learning. One claim that is often made in education is that it is important that students are involved in active learning rather than just being passive recipients of teaching. Constructivist notions of learning suggest that the nature of human cognition is such that teachers cannot simply transfer knowledge to their students by telling them things but rather that a learner has to make their own sense of what they are told – to understand new information in terms of their existing knowledge and understanding (Taber, 2014). Most teachers will recognise that an authoritative and clear exposition of some topic to apparently attentive and engaged students offers no assurance that students will understand and learn the material as intended.

If active learning is 'minds-engaged' learning, then in principle this can involve the teacher talking and the students listening. It is certainly possible in some circumstances for effective learning to occur when students are listening to, and thinking about, a presentation of information. However, this approach usually relies on an engaging teacher able to make a topic interesting to learners and students who are:

- motivated to learn what is being presented;
- well prepared in terms of having the necessary background knowledge (and recognising it as relevant to the materials being presented);
- metacognitively advanced enough to be monitoring their own sense-making as they listen.

In this situation, the learner is undertaking an ongoing internal dialogue between what they hear and their existing knowledge – seeing how things 'fit', looking for inconsistencies, and so on. This can happen but it is not an accurate description of the scenario generally facing secondary teachers with most of their classes.

It is more likely that the dialogic aspects of the learning process, so important to meaningful learning, have to be managed by the teacher who makes the presentation interactive – engaging learners to input their ideas, checking understanding, asking for examples from students' experiences, and so on (Mortimer and Scott, 2003). Good teachers become highly skilled at this: however, it is a mode of teaching that tends to work well in short bursts. Many students, especially in the younger age groups, have quite limited concentration spans. Human learning tends to be incremental and iterative as well as interpretive (Taber, 2014) so effective teaching often means revisiting and developing ideas through regular but brief teaching-led discussions.

In practice, active learning often means learning from and through activities that engage the learner in thinking about their own existing ideas in relation to some new information or unfamiliar example or context. This could involve laboratory work, but need not (see Figure 1). So, for example, DARTs (directed activities related to text) can lead to active learning. DARTS can take many forms but involve the learner engaging with text in a way that requires them to actively think about its content. This could be completing a summary table by referring to text, completing missing words in a text by referring to a diagram (or labelling the diagram from information in the text), and so on. The key point is to provide the information to be learnt but also to require the learner to actively process it. Activities may be cooperative as, for example, in jigsaw learning

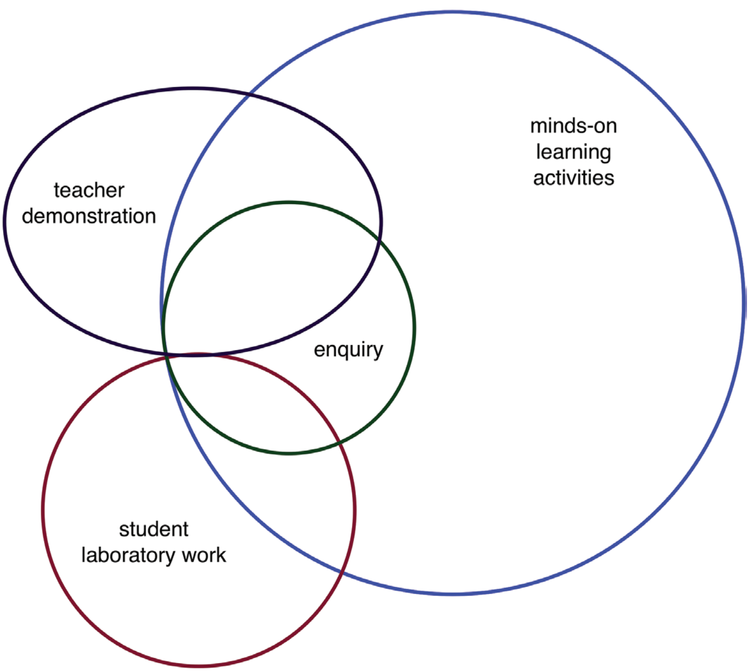

Figure 1 A Venn diagram showing the relationship between some types of activities in chemistry lessons

where different students access different parts of the material to be learnt and have to work together to build up the whole picture. Where it is expected that learners might bring different conceptions of a topic to class, discussion work may be effective in engaging exploration of ideas, for example based around concept cartoons.

In some subjects, such activities might be considered 'practical' work but, in chemistry teaching, the term is usually reserved for laboratory-based activities. Laboratory work may include teacher demonstrations that can engage learners and allow teachers to make clear what is meant to be taken as important in observing some phenomenon (as discussed below). Another term often used in talking about laboratory work is enquiry. The very nature of science is enquiry and it can be argued that if students are to experience school lessons as an authentic reflection of science itself then they need to be involved in enquiry. Certainly the inspection service in England considers that the best science teaching puts '*scientific enquiry at the heart of science teaching*' (Ofsted, 2013: 5). Enquiry involves undertaking activities to actively seek new knowledge and understanding that the learner is genuinely motivated to acquire.

Purposes of laboratory work

Any discussion of how to teach has to consider the purposes of that teaching. A number of possible reasons may be offered to include laboratory work in chemistry classes. These include:

- to engage interest;
- to learn techniques;
- to be part of an authentic community of practice;
- to exemplify theory;
- to understand the nature of science;
- to test ideas;
- to motivate theory.

Laboratory activity can certainly provide opportunities to learn to manipulate apparatus and carry out chemical techniques – if we feel that is important. Safe use of a Bunsen burner, effective use of a filter funnel, accurate use of graduated glassware, and so on, may be considered important for two reasons. For one thing, some students will go on to jobs as technicians or scientists where such techniques are used. However, most students will not. And even those that do may find that the modern research or industrial laboratory seldom uses the kind of hands-on techniques common in school labs. Of course, these techniques are still sometimes practised in chemistry – but for the few that need them on-the-job training is a better option than relying on something you may have carried out years before (and probably with suboptimal kit) in school.

However, learning laboratory techniques is important when those techniques are tools that will be applied for other educational ends. So if we wish students to carry out laboratory work for other purposes (to undertake enquiry, for example) then it becomes important that the students are familiar with the available apparatus, and have the manipulative skills to handle apparatus and materials safely and effectively. When we want students to make up solutions, filter, titrate, crystallise, and so on, in the course of activities that we consider educationally valuable in their own right, then it becomes educationally worthwhile to teach them how to do this.

Authentic learning of the nature of science in the chemistry laboratory

It is sometimes argued that students should obtain authentic experience of the disciplines represented in the curriculum through their learning within school subjects. So, for example, history lessons that simply require students to study the accounts in school textbooks only offer a chance to learn about the *outcome* of historical scholarship and not to experience the nature of *undertaking* historical scholarship. I remember how in primary school some history topics were taught through the provision of document wallets containing resource materials – reproductions of authentic-looking documents contemporary to the historical event being studied. Of course, the primary-age child does not have the skills base to undertake genuine historical scholarship (which does not usually involve having all the relevant documentation sourced, edited and collated into a convenient resource), but *is* given a feel for the authentic work of historians in working with, and needing to interpret and evaluate, primary sources.

In science subjects, there is a danger of science lessons offering only a catalogue of the products of areas of science that seem 'finished': knowledge that has attained canonical status. In principle, all scientific ideas are open to being revisited in the light of new evidence – but that may not be a principle that is always clear from the way science is taught. This is especially so when the curriculum is packed with topics to be 'covered' to the exclusion of sufficient exposure to the processes by which science comes to knowledge, or when assessment regimes imply that rigour in learning science is to be demonstrated by factual recall and application of accepted ideas. An authentic science education offers an impression of what it is to be doing science and to undertake scientific thinking.

Practical work has a major role to play in any authentic form of science education, as the sciences are empirical subjects. In this context there may well be a focus on scientific enquiry, with the suggestion that students need to experience genuine enquiry in the laboratory. As with pupils-as-historians, children and adolescents are not generally equipped to undertake full scientific investigations without a fair level of scaffolding. The potential for open-ended school science practical work to be unproductive if not supported by sufficient guidance was recognised as long ago as 1900 (Jenkins, 1979). Certainly, students are unlikely to rediscover major scientific principles and concepts by being allowed to engage in open-ended exploration in the school chemistry laboratory (something which would in any case need careful oversight in terms of risk assessment). Scientists do not undertake laboratory studies in the usual mode of school chemistry learning – a limited introduction to the theoretical ideas behind the activity, followed by perhaps 30 minutes to 'do the practical'. Scientists rather engage in research programmes where months are spent refining techniques to get their experiments to 'work': they seldom (if ever) turn up one day to work with unfamiliar techniques and materials only to make a major breakthrough. So genuine enquiry that offers authentic experience of scientific work needs extensive engagement with an issue or research problem.

Professional scientific research also relies on creative thought to generate hypotheses and viable research designs just as much as the rational application of logic (Taber, 2011) – and the experience of most scientists is that between the occasional creative breakthroughs much time is spent exploring apparently promising but ultimately unproductive ideas. An authentic science experience would require a long enough engagement with a problem to work through a series of cycles of testing of different ideas. This can happen in some school systems but is inconsistent with packed syllabuses and high-stakes assessments that put a premium on quantity of coverage rather than quality of engagement. So, for example, in schools required to follow the English National Curriculum, such extended project work has largely been restricted to extra-curricular activities such as students attending science clubs working towards CREST awards.

The challenge of learning from laboratory work

It was suggested above that practical work may be undertaken to exemplify theory or to test ideas; however, the linkage between such ideas and the practical itself is not always obvious to students. Chemistry is primarily about substances and their properties and interactions. At first sight, we might think that substances are ubiquitous in everyday life but actually children seldom come in contact with pure samples of substances outside of school chemistry. They may have considerable experience of (to a first approximation) 'pure' water and some experience with samples of pure metals. However, in general, our everyday experience is with materials that are mixtures (such as alloys) and more complex composites (such as wood). Understanding substances is a useful starting point to understanding materials but, by its nature, chemistry deals with a class of things that are already a substantial abstraction from most everyday experience.

Moreover, although chemistry uses many concepts that can be understood in terms of the phenomena that can be observed in the chemistry laboratory (reactions, oxidation, acids, neutralisation, etc.), the theoretical explanations are generally in terms of the chemist's models of matter at a scale well beyond human experience: molecules, ions, electrons, orbitals and the like. These unobservables have to be introduced to learners, who will only be successful in chemistry when they can use these ideas and link them with the descriptive theoretical labels used at the macroscopic scale (Taber, 2013).

As an example, consider the standard chemistry practical to produce sodium chloride by neutralisation. This is a procedure that can readily be undertaken as a student practical. It involves the mixing of sodium hydroxide solution and hydrochloric acid, in the right quantities to give a neutral solution. Evaporation of the solvent (water) leaves crystals of sodium chloride. This is an example of a chemical reaction as we have a different chemical substance after the reaction: sodium hydroxide and hydrochloric acid have reacted and sodium chloride and water have been formed.

Students carrying out this reaction (or 'experiment' as they will often inappropriately but enthusiastically describe it) will need to collect glassware and solutions. They need to check they have bottles with the two different solutions required, and they will have to take suitable precautions such as wearing safety goggles and placing reagent bottles and apparatus on bench mats. They will have to mix the two solutions, and do this in the right quantities. This may involve the use of graduated glassware (requiring specialised handling) or spotting tiles. It will require some form of acid–base indicator to be used. Evaporation of the solution could be left to nature but that means not seeing the product formed (which may be the most satisfying part of the activity); alternatively, there will be a need for heating – perhaps placing an evaporating basin above a beaker containing water (to act as a steam bath) being heated by a Bunsen burner using a gauze and tripod. There is a lot to think about here, and a lot to collate and do – and so potentially much opportunity to be distracted from thinking about the scientific concepts (such as neutralisation).

The reaction may be represented as a chemical equation, either in words or formulae:

hydrochloric acid + sodium hydroxide → sodium chloride + water

$$HCl + NaOH \rightarrow NaCl + H_2O$$

To the chemistry teacher, this is a simple and familiar equation, but research suggests that students find even basic chemical equations quite complex (Taber and Bricheno, 2009) – we might say that they do not have the experience and familiarity with using such representations to 'chunk' the components within working memory as the teacher can. The word equation is complicated by three of the substances having compound names, and to some students the formulae may seem an intimidating form of representation.

In terms of what is observed, the actual reaction involves two clear colourless liquids mixing to give another clear colourless liquid. Indeed, the direct product of the neutralisation reaction is water:

$$H^+(aq) + OH^-(aq) \rightarrow H_2O(l)$$

As the reaction takes place in aqueous solution, the production of *some more water* is not readily detected. Our word equation should acknowledge the presence of solutions:

hydrochloric acid (solution) + sodium hydroxide solution → sodium chloride solution

Sodium chloride (the new substance that can be observed) is not formed until the solvent is evaporated, leading to crystallisation; that is, it is *not* produced during the actual neutralisation reaction. The sodium and chloride ions present in the solution are spectators – they existed, solvated, in the reagents, and continue in much the same state in the solution produced by the mixing. The actual neutralisation reaction then is something (formation of a small quantity of water, in an aqueous solution!) which can be brought about by much student activity in organising and manipulating apparatus and materials in the laboratory – but which is not readily observable (see Figure 2). If an indicator is used to identify the endpoint of the neutralisation then the visible sign of a reaction will be the colour change – a phenomenon that is not *directly* linked to the focal chemical change.

At the theoretical level, we see that the core of this, and other, neutralisations can be understood by invoking interactions between submicroscopic particles (hydrogen and hydroxyl ions) to form other submicroscopic particles (molecules of water). These are theoretical entities that are not observed by the students. What students can observe directly is the crystallisation of sodium chloride in an evaporating basin as the solvent is evaporated on heating. What is apparently observed is a liquid turning into a solid. Actually the solvent from a solution is being driven off, so that the sodium and chloride ions bond under their mutual electrical attraction as they cease to be solvated by water molecules. The theoretical description (evaporation and crystallisation) has to be linked to a phenomenon that at face value looks much like something else (solidification/freezing), and the explanatory model invokes theoretical

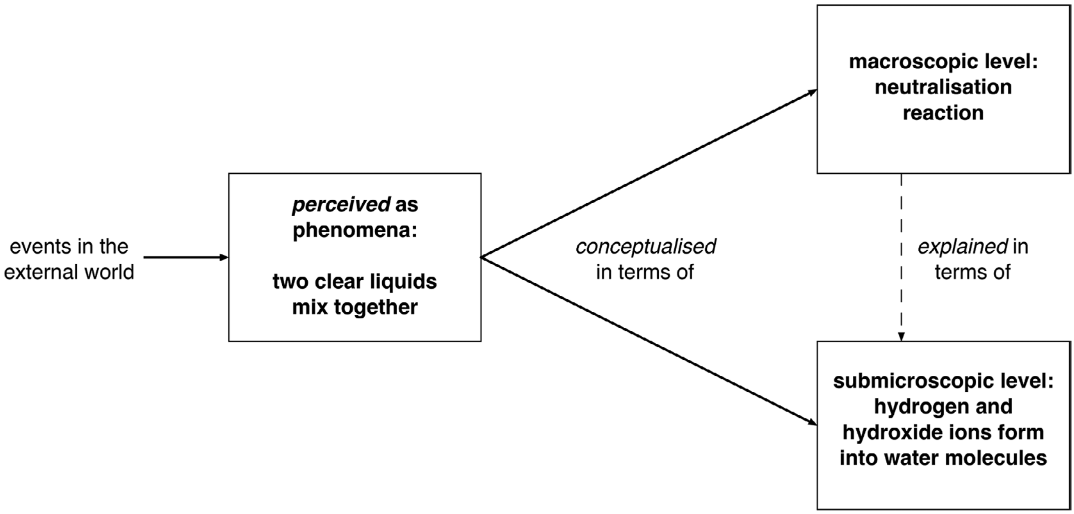

Figure 2 Making sense of neutralisation at two levels; adapted from Taber (2013)

entities that cannot be observed in the practical (see Figure 3).

In this particular case, an added complication is that students may adopt the common alternative conception that ionic bond formation depends upon electron transfer from a metal atom to a non-metal atom – a misconception that may be encouraged by unhelpful statements such as '*atoms bond by either transferring electrons from one atom to another or by sharing electrons*' in official curriculum documents (Department for Education, 2014: 17). The notion of electron transfer is not relevant to ionic bond formation in real chemical reactions such as this neutralisation. However, in terms of *what students can actually see* during the practical work, there is no more basis for explaining the appearance of the solid crystals in terms of ions released from solvent sheaths being attracted together than there is to invoke imaginary electron transfers between atoms that the teacher knows are not actually present in the solution.

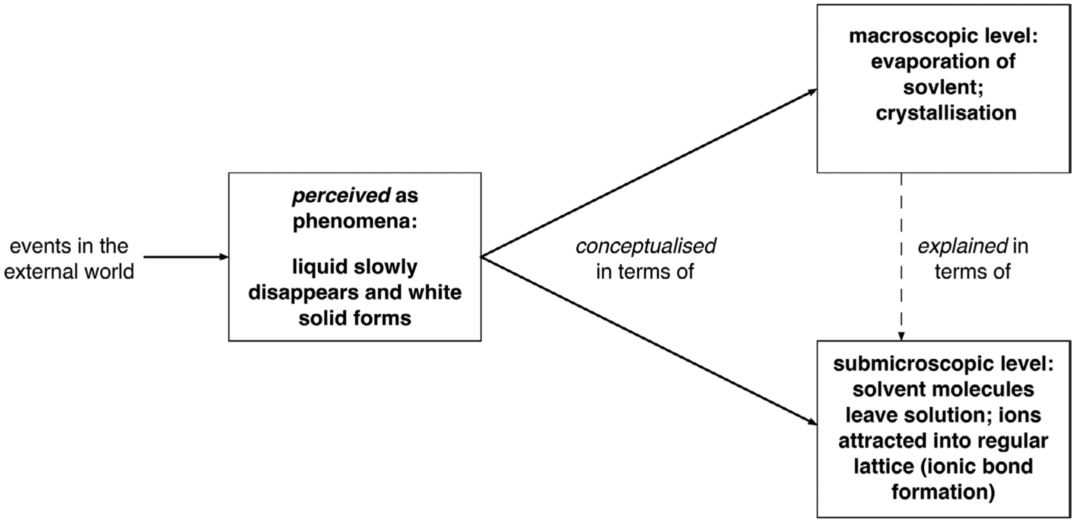

Figure 3 Making sense of crystallisation at two levels; adapted from Taber (2013)

Student practical work or teacher demonstration?

A particular problem then with laboratory work in science is that the phenomena and effects that teachers wish students to gain experience of are often not readily seen by the inexperienced observer. Driver (1983) pointed out that this was a reason why students had trouble rediscovering scientific laws and principles as the patterns scientists seek to explain may not be salient to the casual observer. This is one reason why it is suggested that when undertaking laboratory work it may sometimes be more effective to use teacher demonstrations rather than student practicals. Students will not develop their manipulative skills that way but they will be able to focus on the phenomena that they are meant to observe. It is known that often in student practical work a good deal of the students’ available mental resources are engaged in collecting and organising apparatus and materials, leaving little capacity for thinking about the scientific ideas. This is avoided in demonstrations, and in addition the teacher is able to direct attention to the key features that need to be observed and help learners interpret their observations in terms of the correct language and ideas. The vicarious *man*ipulation of the practical by the teacher may give increased scope for student *ment*ipulation of the relevant chemical concepts. Learning to be an effective presenter of chemical demonstrations requires some practice but advice about well-established demonstrations is available (Lister, 1996).

When should student practical work be used in teaching chemistry?

Many students enjoy laboratory practices and are genuinely fascinated by chemical changes and (despite the disappointing evidence that students rarely recall many details of practical work) there are some phenomena that do tend to be recalled well by many students – the colours of flame tests and the smells associated with substances such as ammonia and hydrogen sulfide, for example. Yet teachers need to be aware of the difficulties of learning chemical ideas from student laboratory work if they are to plan student practicals to support effective learning.

The issue is not whether student laboratory work has a place in chemistry teaching – it certainly does – but when the commitment of resources (in particular class time) to this type of activity is going to be most productive. Given the difficulty of learning to perceive what can be observed in the laboratory in terms of the two levels of re-description used by chemists (concepts such as reaction, neutralisation, crystallisation; models of substances and their interactions at the level of ions and molecules), it is important to ensure that what is observed during practical work can be actively linked in students’ minds with the theoretical descriptions and explanations.

As many reactions of interest happen too fast (such as the hydrogen–oxygen explosion) or too slowly (such as the rusting of iron) to be readily observed directly, the use of modern digital technology may be employed to use freeze-frame and time-lapse filming techniques. Where students can carry out open-ended extended enquiry work then learning to keep a well-organised laboratory notebook is valuable; however, where stand-alone practicals are undertaken to illustrate specific chemical ideas it may often be more sensible to find alternative modes of recording that help students focus on linking key observations with theoretical ideas.

DARTs can be designed as scaffolds to use in practical work that help direct learner attention towards the specific observations, concepts and models that need to be related so that the mental resources that are available to focus on ‘theory’ are not tied up in unnecessary writing. Sometimes it may be useful to get learners to draw a diagram or prepare a results table *before* starting a practical to focus their minds on what needs to be recorded, but during the practical it may be more productive to have students make small but key additions to documentation provided by the teacher (for example, see Figure 4). Finding ways to link actual practical activity with the use of simulations of the relevant molecular-level description can be productive. For example, students could be tasked with capturing the chemical phenomenon with a sequence of images from a digital camera (perhaps on a smartphone or tablet) that can be imported into a document alongside images from a suitable simulation of the changes occurring at the molecular level.

Using practical work to introduce phenomena to motivate the need for theory

One of the possible purposes for practical work listed above is *to motivate* theory. Ultimately,

The reaction between magnesium metal and copper ions

In this reaction magnesium will displace the less reactive copper from its compound copper nitrate. Copper metal will be precipitated; and magnesium nitrate will remain in solution.

MAGNESIUM + COPPER NITRATE → MAGNESIUM NITRATE + COPPER

This is an example of a d____________________ reaction

(or a c____________________ reaction)

Apparatus and materials: boiling tube, thermometer, copper nitrate solution, magnesium powder, spatula, watch glass, clamp, boss and stand, stirring rod, conical flask, filter funnel, filter paper.
Access to chemical balance, and chemical oven.

Note: powdered magnesium is used rather than magnesium ribbon because

____

Method (1): Clamp the boiling tube in a horizontal position.
$^{2}/_{3}$rd fill the boiling tube with copper nitrate solution. Place the thermometer in the solution.

Observation: colour of solution: ____________________________

Measurement: temperature of solution: ____________________________

Method (2): Using the watch glass weight out about 0.48 g of magnesium powder.

Measurements:
mass of watch glass .... __________ (a)
mass of watch glass + powder .... __________ (b)
∴ mass of magnesium powder .... __________ (b-a)

Calculation: A_r (Mg) = 24
1 mole of magnesium has a mass of 24 g
∴ 0.48 g of magnesium contains $^{0.48}/_{24}$ moles = __________

Method (3): Add the magnesium powder to the solution. Carefully stir the mixture. Note the highest temperature reached.

Measurement:
highest temperature of mixture: _______
temperature rise: .... _______

Note this is an ____________________ reaction.

Observation: Colour of reaction mixture: ____________________
We may infer that ____

Method (4): Weigh a piece of filter paper. Now collect the displaced copper by carefully filtering the reaction mixture. Place the filter paper and copper into an oven to dry before reweighing. (If time allows: dry to a constant weight)
Note: the paper is dried because __________________________________

Measurement:
mass of filter paper + copper __________
mass of filter paper __________
∴ mass of copper displaced __________

Calculation: A_r (Cu) = 64. How many moles of copper have you collected?

____

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Conclusion: ____

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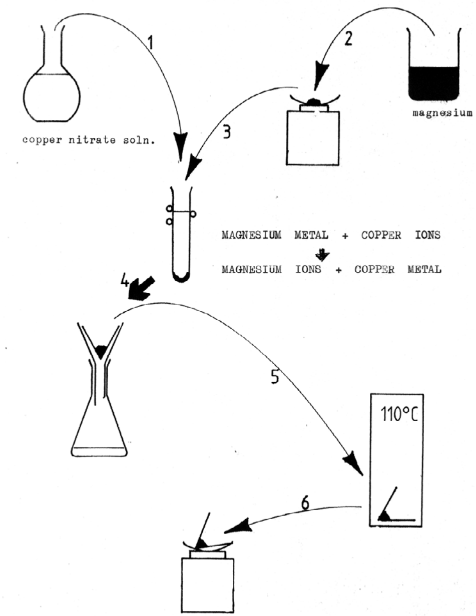

FLOWSHEET. This sheet should provide an 'overview' of the experiment to guide you through the procedure; and to act as a 'cue' for revision.

Figure 4 Practical 'hand-outs' can support students in appreciating the logic of a procedure and help them to focus on making observations and drawing inferences chemistry, like other sciences, has at its core a dialectical relationship between empirical investigation and theory development. Authentic chemistry teaching should then use practical work to help students link ideas and evidence to find theoretical descriptions and explanations for natural phenomena. Given the difficulty of clearly observing many chemical concepts, there is much to be said for seeking to prioritise the epistemic relevance of chemical theory; that is, to start from phenomena that will interest students, and then draw upon the resulting 'awe and wonder' to culture the epistemic hunger (the need to understand) that drives scientists.

So, rather than using practicals to illustrate theory when the links to theory are often not readily obvious to learners, we can sometimes start from phenomena that will intrigue students and use that as the grounds for seeking explanations ('what is going on here?'), and only then introduce the theory. It will not always be sensible to teach that way but the approach can help learners appreciate *why* scientists develop theory and *where* theory comes from, and so appreciate the nature of scientific knowledge as conjectural and a creative product of human imagination (Taber, 2011).

Conclusion

There are many places in a chemistry course where student practical work can both engage and – with suitable teacher scaffolding – inform students. Some school chemistry topics more readily lend themselves to student practical work than others (see *Further reading*). However, as discussed in this article, there can be significant barriers to teaching through student practical work in chemistry. Good chemistry teaching engages learners in thinking deeply about chemical concepts and models. Sometimes student practical work can achieve this; sometimes a teacher demonstration is better. In some concept areas, more effective teaching may employ pedagogy that requires students' minds to be active without laboratory work. Part of the expertise involved in effective chemistry teaching is knowing when it will be productive to use laboratory work, and how to frame laboratory work to meet different educational objectives. When done well, and for the right reasons, practical work retains its central role in chemistry classes.

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Further reading

Chapters in the ASE Science Practice handbook *Teaching Secondary Chemistry* (2012, Hodder Education) offer advice on suitable practical activities for teaching key chemistry topics.

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