Practical investigative work in secondary education

How can the planning and undertaking of practical investigative work be approached with students through a structured dialogue between teacher and students?

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Much of the inefficiency of the practical work undertaken in schools can be attributed to its presentation in a closed format, in other words, as a set of instructions that the students must follow without being given the opportunity to understand the problem to be resolved or how it can be resolved, or its importance in relation to the theoretical models developed in science classes. Faced with this method of presenting practical work, an open way is proposed in which the problem to be resolved is posed, framed within the construction of the pertinent chemical model and students are helped to think about how it can be resolved through a series of structured questions, which constitute the basis of a dialogue between teacher and students and between the students themselves. This didactic proposal is a call for undertaking practical investigative work that approaches significant problems in the development of theoretical school models. It is illustrated through the posing and resolution of two problems that play an important role in the preparation of the atomic-molecular model of matter: the determination of the relative atomic mass of an element and the determination of the molecular mass of a substance.

The different aims of practical work

There is a great deal of consensus about the importance of experimental work in science teaching, which does not mean that there has not been or still is a debate about what the fundamental objectives of the practical experimental activities should be. Various authors (Woolnough and Allsop 1985; Hodson 1994; Corominas and Lozano 1994; Gott and Duggan 1995; Leite 2001; Izquierdo, Sanmartí and Espinet 1999; Sanmartí, Márquez and García 2002; Millar, Le Maréchal and Tiberghien 1999; Caamaño 2003) have set out the diversity of ends for which practical work in science classes is used and have proposed some kind of classificatory outline in relation to the different objectives sought.

Different functions of experimental practical work in chemistry

Whatever practical work outline is followed, we believe that the practical experimental work in chemistry classes should permit:

1. *Bringing experimental evidence to the learning of the concepts (illustrative function of the concepts)*
2. *Interpreting phenomena and experiences based on conceptual models (interpretative function of experiences)*
3. *Learning the use of the instruments and the basic techniques of the chemistry laboratory (function of learning laboratory methods and techniques)*
4. *Developing methods to resolve theoretical questions in relation to the construction of the models (investigative function related with the resolution of theoretical problems and construction of models)*
5. *Developing and applying methods to resolve questions of a practical nature contextualised in everyday environments of chemistry and applied chemistry (investigative function related with the resolution of practical problems)*

A classification proposal

Based on classifications proposed by Woolnough and Alsop (1985) and Gott and Duggan (1995), we can classify practical work into experiences, illustrative experiments, practical exercises and investigations (table 1). Within this outline it could be useful to sub-classify the practical exercises into procedural and illustrative, and the investigations into investigations to resolve theoretical and practical problems (Caamaño 2004). Let us look in more detail at the objectives of each one of these kinds of practical work.

- **Experiences** play an outstanding role in the perceptive knowledge of the phenomena (**perceptive experiences**) and offer greater interest if they are complemented by interpretative demands of the phenomena observed (**interpretative experiences**), with exploratory ends about the ideas of the students.
- **Illustrative experiments** are useful for bringing experimental evidence to the formation of determined concepts, and to the illustration of laws or principles. It is also important here to encourage curiosity about what will happen before they are carried out and involve the students in the interpretation of the phenomena shown. If emphasis is placed on the interpretative aspect, more than the illustrative, there is little difference between the interpretative experiences and illustrative experiments, other than the more frequently qualitative nature of the former. Both can also be used as demonstration by the teacher and discussed and interpreted with the whole class group.
- **Practical exercises** are used to learn determined practical skills and processes (**procedural exercises**) or to experimentally check relations between variables, already known at a theoretical level (**illustrative or corroborative exercises**).
- **Investigations** serve to learn how to plan and carry out small scale investigations in the course of the resolution of theoretical problems (**investigations to resolve theoretical problems**) or of practical problems (**investigations to resolve practical problems**).

***Table 1**. Kinds of practical work*

- *Perceptive and interpretative experiences*
- *Illustrative experiments*
- *Practical exercises*
  - *To learn practical skills and processes*
  - *To corroborate the theory*
- *Investigations*
  - *To learn to investigate and resolve theoretical problems (in the framework of the preparation of models)*
  - *To learn to investigate and resolve practical problems (application of models)*

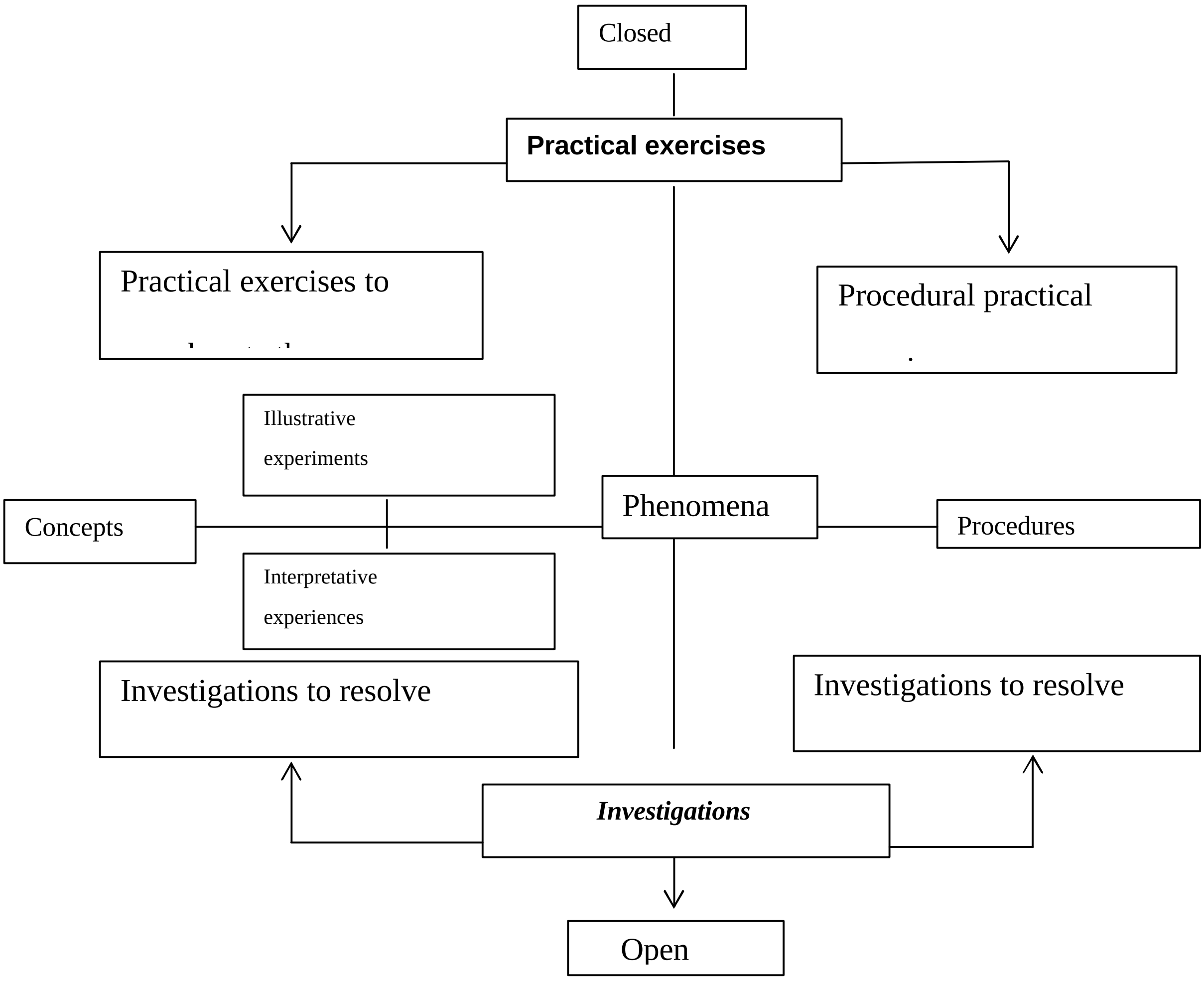
Practical procedural exercises mean an atomist vision of the learning of the procedures that involve a gradation of the learning of the procedures before investigating, while **practical corroborative exercises** involve a vision of the practical work that does not allow students to consider what the problem really is or the methods to resolve it. In contrast, **investigations** to resolve both theoretical and practical problems involve a holistic (global) vision of learning of the procedures, making possible better conceptual and procedural understanding of science, and are much more motivating activities.

Investigations to resolve theoretical problems have the principal objective of bringing experimental evidence to the formation of scientific school models. They allow the contrasting of hypotheses and the determination of properties within the framework of theories in process of school preparation, in addition to involving a procedural understanding of science. Examples of this kind of practical work would be to investigate how the volume of a gas varies with the temperature in the development of a kinetic-corpuscular model of the gases, or how we can determine the relative atomic mass of an element in the development of the atomic-molecular model.

Investigations to resolve practical problems have the principal objective of procedural understanding of science and its practical contextualisation. They are investigations to resolve problems posed in the context of everyday life or of the practical applications of science. For example: Which detergent is more efficient? Which is the best antacid out of various? How much iron does a pill to combat anaemia contain?, etc.

Table 2 shows the relation between the different kinds of practical work proposed, in accordance with two axes: degree of openness (closed-open) and relative importance of the concepts and the procedures (concepts-procedures):

Table 2. *Relation between the different kinds of practical work (Caamaño 2004)*



The special importance of the practical investigative work and the integration of practical work in the construction of models

Various authors (Qualter et al. 1992, Watson 1994, Carrascosa 1995, Gott and Dugan 1995; Gil and Valdés 1996: Oldworthy and Watson 2001; Martins 2002; Caamaño 2002, 2003; Gárritz and Irazoque 2004) have defended the interest of the use of practical investigative work in science classes. Some of them have advocated the integration of this practical work as an essential activity in the preparation of scientific models in school (Gil and Valdés 1996; Sanmartí, Márquez, García, 2002; Carrascosa, 1995; Leite and Figueroa, 2004; Caamaño and Maestre, 2004). Others (Gil et al. 1999; Gárritz and Irazoque 2004) have noted the coincidence of objectives of open practical work with the preparatory activities of conceptual models and resolution of problems and have suggested the appropriateness of integrated planning and undertaking of these activities.

In different articles we have dealt with how to transform traditional practical work into practical investigative work (Caamaño, 2002), and how to approach jointly with students the planning stage of practical investigative work (Caamaño and Corominas 2004). A more recent work (Caamaño and Maestre 2004) focuses on the development of the practical activities in the chemistry courses that use interpretative experiences and theoretical and practical investigations in the development and application of the fundamental models in chemistry. In this paper we will attempt to present this line of work from a perspective that takes into account all the practical investigative work that can arise in the development of the atomic-molecular model of matter.

A process of dialogue for the planning of investigations

We can consider that investigations that seek to determine the value of an important property within the development of a model go through the following **phases**:

1. The phase of posing and perception of the problem, in which the teacher poses and contextualises the problem to be resolved, and the students must understand and conceptualise it.
2. The planning phase in which the method that can be used must be decided and the experimental procedure and the calculations that it will be necessary to carry out must be planned, until achieving a global vision of the investigation. It is in this phase that we propose a sequence of structured questions that guide the teacher-student dialogue, which should lead to a joint preparation of the resolution procedure.
3. The realisation phase, which involves mounting the experiment, the taking of measurements and the numerical, graphic or computer analysis of the data.
4. The evaluation phase, which involves the valorisation of the result or results obtained and the analysis of their plausibility, comparing them with the results obtained by other groups and with the values that can be tabulated.
5. The presentation phase, which involves the writing of a report and, whenever possible, the oral presentation of the research undertaken.

In the description of the investigations that we will undertake next, we will try as far as possible to reproduce the dynamic established in the classroom when these kinds of problems are posed, planned and resolved. We will particularly focus on the first two phases: the **posing** of the problem and its **planning**. Our description of the planning phase corresponds to a dialogue between the teacher and the whole of the class group, based on **key structured questions** put to the students to help them design a method of resolving the problem. This dialogue can be held with the whole of the class group (around 15-20 students), immediately after posing each one of the questions (in a dialogue that allows the joint preparation of the procedure to be followed) or after having allowed the students to think for a certain period of time, while they work in pairs or groups. The difficulty of the foundation of the method will condition how far we guide students in this initial phase. In the examples described, the conceptual foundation of the method is presented by the teacher while the more specific questions of the experimental procedure it will be necessary to apply are posed to the students.

Practical investigative work integrated into the construction of the atomic-molecular model of matter

Some of the questions that can be approached through interpretative experiences and investigative experimental activities in the construction of the atomic-molecular model of matter are:

- How are different substances identified?
- How can we find out if a substance is a simple substance or is composed of other simpler substances?
- How is the permanence of an element in a cycle of chemical reactions demonstrated?
- Which properties are useful for organising and classifying chemical elements?
- How can we determine the relative atomic mass of an element?
- How can we find out what the formula of a composite is?
- How can we determine the relative molecular mass of a substance?
- How can the volume of a molecule be estimated?
- How can the number of molecules of a sample of a substance be estimated?
- How can the Avogadro constant be estimated?
- How can we find out experimentally if a substance is molecular or is formed by a giant structure?
- How can we provide experimental proof of the existence of ions in solution?
- How can the independent behaviour of ions in a solution be shown?
- How can the electrical charge of an ion be determined experimentally?
- How can we distinguish experimentally between molecular, covalent, ionic and metallic substances?
- How can we differentiate experimentally between polar and apolar liquids?

All these questions are intimately related to concepts and models that are developed to classify the material and construct the atomic-molecular model: substance, chemical reaction, simple substance, composite, chemical element, atom, molecule, ion, molecular structure, giant ionic, covalent and metallic structure, etc. Depending on how they are posed they can serve us to contrast hypotheses in the construction of the atomic-molecular model, as a contribution of experimental evidence of already established hypotheses or as a way of obtaining better understanding of the characteristics of the model. The high degree of openness with which it is proposed that the investigations to answer these questions are undertaken also means that they will be useful for the learning and understanding of investigative strategies.

A description of this practical work can be found in the dossier Treballs pràctics de Química. Batxillerat (Caamaño and Corominas 2002), which can be consulted on-line, even though not all the outlines have the open form we propose here. In contrast, a clear example of integration of the interpretative and investigative practical work in the development of a model is the didactic proposal of construction of the concept of ion and of the electrolyte model based on the interpretation of electrolysis and the properties of the solutions of electrolytes, developed by the Grup Recerca (1983) (Caamaño and Maestre 2004). The construction of the model involves questions like the following: How can the electrical conductivity of the solutions of electrolytes be interpreted? How can we have evidence of the migration of ions in electrolysis? What happens to ions when they reach electrodes? How can we determine the ion charge? Are there already ions in the solution of an electrolyte before the passing of an electric current? Can ions exist before the dissolution of an electrolyte in water?, etc.

Next, two open outlines for the following investigations are shown:

- How is the relative atomic mass of an element determined?
- How is the relative molecular mass of a substance determined?

Table 3. *Outline of structured questions to plan the investigation: How is the relative molecular mass of the acetone determined?*

How is the relative molecular mass of the acetone determined?
Setting of the problem *This means conceiving a method to determine the molecular mass of the acetone, a volatile liquid, which can be easily vaporised, which changes the problem to one of how to determine the relative molecular mass of a vapour (gas).*
Planning: Foundation of the method *Direct measurement of the relative molecular mass of molecules of a gas is not possible, so we will have to think of an indirect measurement method, through a property that we can measure with which it is related.* o *What property of a gas is related to the mass if its molecules? Have you ever observed the different behaviour of the gases depending on their density (mass / volume) with respect to air, for example, when a balloon is inflated and set free?* o *The Avogadro hypothesis says that equal volumes of two different gases contain the same number of molecules. What relationship do you think there will be between the masses of equal volumes of two gases and their molecular masses? To help you answer you can visualise the situation by drawing two different gases enclosed in two recipients of equal volume, in which you represent the same number of molecules of each one of them.* o *Think about how we could calculate the molecular mass of the acetone through the comparison of the mass of two equal volumes of vapour: one of acetone, and another, also of a volatile liquid, such as ethanol, of known molecular mass*
Planning: Experimental design of the method o *What method can we use to volatilise a volatile liquid? What recipient can we use to vaporise each liquid and collect the vapour?* o *How can we make the vapour produced gradually emerge from the recipient dragging the air inside it so that, in this way, the recipient is full of vapour at atmospheric pressure?* o *How can we be sure that the temperature of the vapour is the same in the two measures, with the acetone and with the ethanol?* o *How can we determine the mass of the vapour that fills the whole of the recipient?*

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Table 4 *Outline of structured questions to guide the planning and undertaking of the investigation: How is the relative atomic mass of magnesium determined?*

How is the relative atomic mass of magnesium determined?

Setting of the problem

Historical contextualisation of the problem and of the kind of method used.

Planning: foundation of the method

- *What indirect measurement method can we use?*

Planning: experimental design of the method

- *Design a method that allows the measurement of the relative atomic mass of magnesium, write it down in your notebook, making use of the drawings that may be necessary, and discuss it with your teacher before putting it into practice.*
    - *What reaction can we use?*
    - *What measurements and calculations are necessary?*
    - *How are the mass of magnesium and the mass of hydrogen measured?*
    - *What quantity of magnesium is it appropriate to use?*
    - *What is the most appropriate concentration of hydrochloric acid?*
    - *How can we collect hydrogen gas and measure its volume?*
    - *How can the mass of hydrogen based on its volume be calculated?*
    - *How can the experimental device to avoid hydrogen loss be improved?*
- *Make a definitive outline of the procedure and the device you plan to use and a list of the material and products you need.*

Experimental realisation

- *Mount the experimental device, carry out the reaction and measure the mass of the magnesium and the volume of the hydrogen gas obtained at atmospheric pressure.*

Data processing

- *Make the calculations to obtain the value of the relative atomic mass of the magnesium.*

Evaluation of the result

- *Is the result plausible?*
- *Compare the result obtained with a tabulated value.*
- *Calculate the relative error committed. What could be the causes of the error?*

Presentation of the investigation

- *Write a report describing the investigation undertaken and the result obtained.*
- *Prepare an oral presentation of the investigation undertaken with the help of slides or power-point.*

Conclusion

The structured questions we have posed allow progress in the resolution of the problem jointly with the students. Some have allowed understanding of the problem to be resolved and thinking of a method of resolution, others have allowed the specification of the procedure, deciding which variables had to be measured and how they had to be measured; others have allowed us to think about corrections or alternative devices to improve the exactitude of the result; lastly, some have allowed us to obtain and evaluate the result.

Throughout each investigation the students have been "accompanied" by the teacher. The presentation phase of the problem and planning of the method can well have taken place in the classroom; the realisation phase of the experience must necessarily take place in the laboratory; and the data processing phase, and that of obtaining and evaluating the result, may well again take place in the classroom. Students record in their notebooks everything the teacher puts to them, and the solutions and the methods proposed in order to find the appropriate method. Also the design they will apply, the measurements and calculations made, and the final result obtained. Only when the final phase has been completed can the students be asked to produce a written report or an oral presentation that synthesises the research undertaken.

As we said at the outset, much investigative work shows that the main cause of inefficiency and lack of motivation in practical work results from a closed presentation of these activities through "cookery recipe" type outlines. The answers to the questions posed in the planning of the investigations we have just considered are precisely those resulting from the closed protocols of traditionally used practices. So it is about questioning each action to be undertaken jointly with the students, in place of simply giving them instructions without further comment. Moreover, teachers wishing to offer students a more extensive initial orientation for the undertaking of the investigation we have proposed here would gain much if in place of a series of instructions they offered a document with the structured questions and answers that we have given as examples.

The open outlines proposed, which can be accompanied by help sheets and by some guidelines for teachers, are an excellent way of presenting in writing an investigative work and guiding its resolution. However, in our opinion, its greatest use lies in suggesting the questions that the teacher can put to the students in the form of a dialogue to jointly plan the investigation. A less open outline could also be followed by students by themselves after a presentation with later contributions from the teacher. Clearly there are many levels of openness possible and of ways of using these outlines, according to the type and complexity of the investigations proposed and the degree of conceptual and procedural knowledge of the students.

The principal objection to a more open approach such as what we have just proposed is that it demands more time. And this is true. However, is it not perhaps better to do less practical work and for this to be more beneficial and illustrative of what scientific work is? Another fundamental difficulty for the incorporation of this open approach in practical work is that it involves a change of mentality in terms of the teacher's task in practical classes. On this last point, we believe that only the opportunity to have shared experiences in seminars and workshops with other teachers, to reflect as a team and experience with students these more open approaches, can allow us to advance in the transformation of practical work into a more motivating, creative and efficient activity for the learning of conceptual and procedural understanding of science.

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