Teaching and Assessing the Nature of Chemistry

Ensenyar i avaluar la naturalesa de la química

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abstract

In science textbooks, the scientific method is often presented as a linear and stepwise process that involves hypothesis testing and experiments. Yet history of chemistry illustrates the diversity of methods that also involve non-manipulative observations. The article discusses Brandon's Matrix that provides a tool for highlighting the diversity of methods in chemistry. Example resources produced by Project Calibrate in England are presented to illustrate how students' epistemological commitments, metacognition and critical thinking in chemistry can be enhanced.

keywords

Nature of Chemistry, methods in chemistry, Brandon's Matrix, Project Calibrate.

resum

El mètode científic sovint es presenta, als llibres de text de ciències, com un procés lineal i gradual que implica contrastar hipòtesis i realitzar experiments. No obstant això, la història de la química ens mostra una diversitat metodològica que inclou també observacions no manipulatives. L'article considera la matriu de Brandon com una eina que permet ressaltar la diversitat metodològica de la química. Es presenten exemples de recursos desenvolupats pel Project Calibrate a Anglaterra per il·lustrar com es poden millorar els compromisos epistemològics dels estudiants, la metacognició i el pensament crític en la química.

paraules clau

Naturalesa de la química, mètodes de la química, matriu de Brandon, Project Calibrate.

Introduction

Chemistry is a fascinating subject. This is why we have chosen to study it and this is why we continue to engage in it through education, eager to pass on our knowledge to the next generations. Chemistry is a subject that takes us into an invisible world of atoms, molecules and chemical reactions. It helps us make sense of the materials and provides us with tools to synthesise new substances. We use symbolisms to help us communicate about the intricate details about the material world. But what *exactly* is chemistry and how do we know how to define what chemistry is about? These questions may seem unnecessary when we have a functional and pragmatic way of navigating the conceptual and methodological landscapes of chemistry, but they are nevertheless important to pose. They are important because they give us a different perspective on chemistry. It helps us have a bird's eye view of how chemistry works. In a sense, the perspective that we get from fundamental questions like «what is chemistry?» is a bit like having a map of a city where we can be oriented to the details such as buildings, rivers, landmarks, roads, parks and such, and we can appreciate the collective endeavour. Without a map, we may understand what rivers and roads are, and what purposes they serve in a city, but we would not appreciate the relational connections between spaces and objects in the landscape. We would not have a holistic understanding of and orientation to the city. The analogy with chemistry is that we may emphasise concepts, processes, mechanisms and all that is conventionally part of the chemistry curriculum. Yet, without an overall 'map' of

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chemistry where we are having a meta-level perspective on the subject, it's suspect if and how we can understand the significance of the chemical concepts and processes in the first place. When we ask, «what is chemistry?» we are going deeper into understanding chemistry, what makes chemistry *chemistry* and how we know what chemistry is.

Teaching the epistemic core of chemistry

When we ask, «what is chemistry?» we are really asking a philosophical question. *Philosophy of chemistry* is a line of scholarship that interrogates such fundamental questions (Erduran, 2014; 2013). Within science education research, there is also a line of research called *nature of science* that addresses such questions (Erduran & Dagher, 2014). In a recent book (Erduran & Kaya, 2019), we have explored how ideas from philosophy of chemistry may be incorporated into chemistry teacher education through reflections on the nature of chemistry. We discussed the «epistemic core» of chemistry: those aspects of chemistry that

Aspect of Epistemic Core	Epistemological commitments	Metacognition	Critical thinking
Aims and values	Students appropriate a set of epistemic aims and values from chemistry such as commitment to accurate and objective evidence	Students are aware of their use of epistemic aims and values of chemistry in their investigations	Students can evaluate whether or not chemists' claims are in line with their projected epistemic aims and values
Practices	Students are committed to employing appropriate chemical practices such as modelling and classification in investigating problems	Students can evaluate their understanding of chemical practices such as modelling and classification	Students can compare and contrast the strengths and limitations of different practices such as experimentation and observation
Methods	Students value the importance of diversity of methods in chemistry ranging from hypothesis testing to non-manipulative observation	Students can distinguish between different methods in chemistry and select them to be fit for purpose in problem-solving	Students can advance arguments for and against the use of a particular method to investigate a problem
Knowledge	Students understand that chemistry relies on different forms of knowledge such as theories, laws and models, and that these knowledge forms develop in time	Students can evaluate their own chemistry knowledge and characterise it relative to established theories, models and laws in chemistry	Students understand the explanatory power of chemistry knowledge as well as its limitations

Table 1. Potential benefits of learning the epistemic core of chemistry (from Erduran & Kaya, 2019).

concern the development of chemical knowledge. The epistemic core is about the aims and values, practices, methods and knowledge in chemistry. The epistemic aims and values relate to criteria like objectivity and accuracy that help chemists establish the reliability of chemical knowledge. The practices are about the ways in which chemists engage in knowledge construction, for instance through modelling through explanations and predictions of chemical reactions. These practices may involve observation, classification and experimentation. The methods are about the various approaches to the research process including whether or not hypotheses are being tested, and whether or not particular variables are being changed. Chemical knowledge comes in the form of theories, laws and models. These forms of knowledge help us together to make sense of chemical phenomena. In Erduran and Kaya (2019) we highlighted how the teaching and learning of the epistemic core of chemistry may benefit students (see Table 1). For example, learning the epistemic aspects of chemistry can potentially help clarify students' epistemological commitments, improve their metacognition and foster their critical thinking.

Focusing on the Diversity of Methods in Chemistry

Let's focus on one aspect of the epistemic core of chemistry: methods. What are methods in chemistry? There is a long tradition of representing the scientific method as a linear and stepwise process that involves hypothesis testing. Blachowicz (2009), for example, reviewed 70 introductory science textbooks and demonstrated that textbooks tend to present the scientific method as a stepwise process in a simple empiricist view of science. More recently, Woodcock (2014) discussed such «myths» of the scientific method as a simple process of following some steps which may include observing, making a hypothesis, experimenting, analysing data, confirming or rejecting the hypothesis and making conclusions. Figure 1 illustrates some examples from

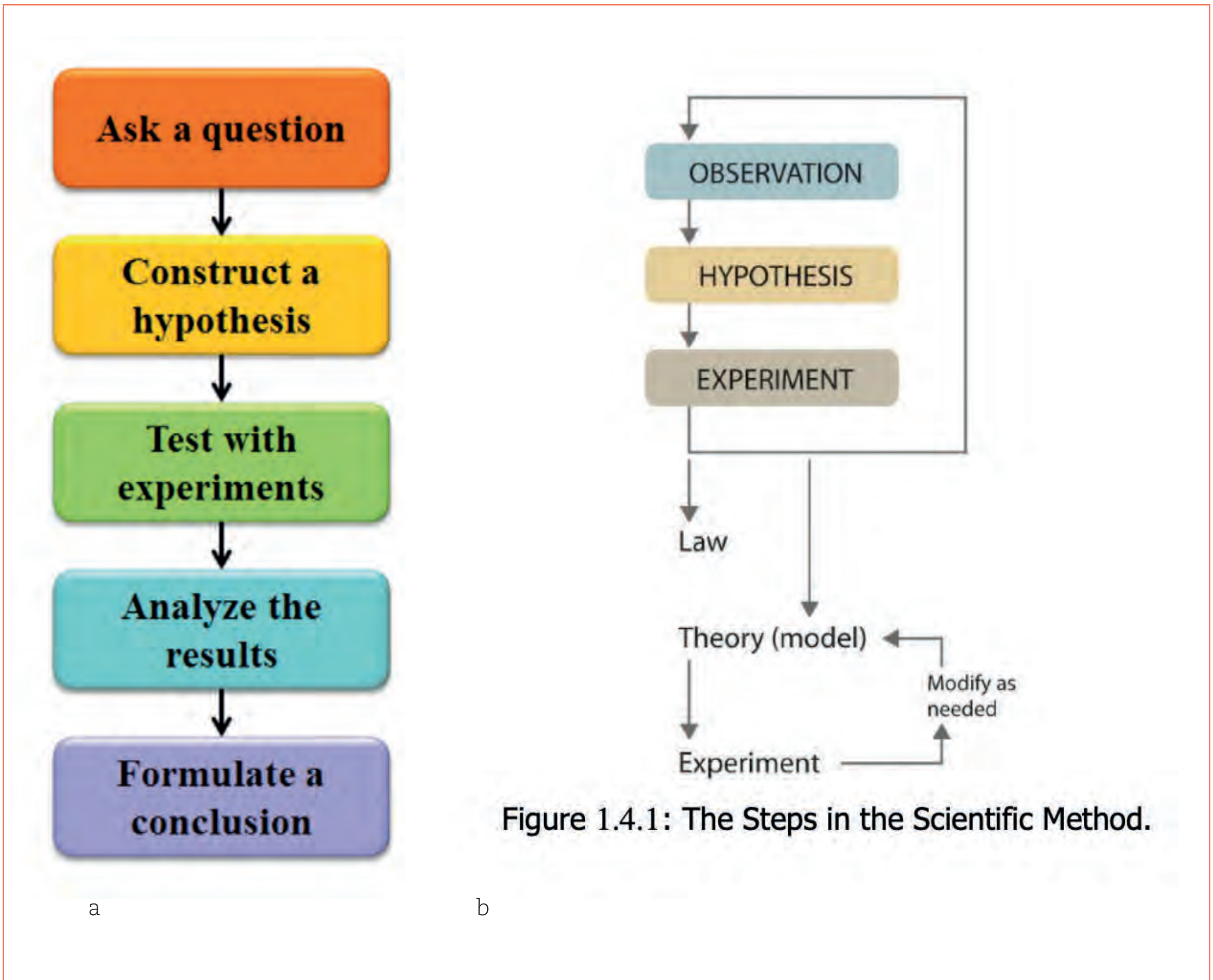

Figure 1. Model of the scientific method as depicted by (a) GetChemistryHelp (2021) and (b) Chemistry LiberTexts (2021).

educational resources available freely online. As the figures demonstrate, such models of the scientific method rely heavily on the presence of hypothesis testing through experiments.

However, when we turn to studies in philosophy of science, we witness that such simplistic models of the scientific method are not representative of how methods actually work in science. Brandon (1994), for example, provided an account of scientific methods that demonstrate that not all experiments rely on hypothesis testing. He represents the connections between experiments and observations in terms of a matrix (i.e. two-by-two table) in which the nature of the investigation (experiment/observation) is related to whether it involves manipulation of variables or not, and whether or not it involves hypothesis testing or parameter measurement. Table 2 refers to the terms that Brandon himself used and some examples from chemistry that Erduran and Dagher (2014) provided to match each category. In this paper, in order to be able to use the terms in different ways in the text, manipulate or manipulation are used interchangeably, and they relate to the changing of variables. Measure or measurement of parameters refer to the noting of data from investigations.

So in Brandon's Matrix of scientific methods, we thus can ask two questions: (a) are we testing a hypothesis or not? and (b) are we changing (manipulating) variables, or not? If we are not testing a hypothesis, we might simply be making observations or measuring some parameters. If we are not manipulating variables, we may just be describing our observations. Erduran, Childs and Baird (2020) gave the following contemporary example in relation to the COVID-19 pandemic to illustrate how Brandon's framework can be applied to different problems in science. Scientists may collect data around how the virus might be influencing a patient's breathing over a period of time. Such observations are simply based on the recording of parameters where there is no manipulation of variables in the sense of an experiment (non-manipulative parameter measurement). Likewise, sometimes data might be subjected to hypothesis testing about correlation between incubation period and extent of lung disease, but without having been part of an experiment (non-manipulative hypothesis testing). Scientists may carry out some randomised control trials in which a drug or a vaccine is treated as a variable in interventions that also include control groups to test the placebo effect (manipulative hypothesis testing). Sometimes scientists may simply change variables in order to make observations but they don't have specific hypotheses in mind (manipulative parameter measurement). The important point is that all these different approaches are essential when doing science, and there is no one single method but rather a diversity of scientific methods.

Erduran and Dagher (2014) gave the example of how Mendeleev predicted the existence of the element gallium without manipulating any variables but rather by reasoning about atomic weights. This is an example where a prediction was made based on known elements. De Boisbaudran subsequently and independently characterised the new element spectroscopically. De Boisbaudran was testing the hypothesis of the existence of a new element by spectral analysis of an ore and managed to isolate gallium through this method. Again, there was no changing of variables but this time, there was testing of a hypothesis about a new element. Other chemists such as Rutherford and Crookes engaged in a range of other methods. All together the use of such diversity of methods led to the formulation of the Periodic Table of Elements. Brandon's Matrix does not imply that all investigations have to fit into one quadrant exclusively. In fact, Brandon himself argued that many investigations lie in some kind of a continuum across these ways of doing science.

Another example about Brandon's Matrix is the following. When an experiment is conducted to measure the effect of temperature on the pressure of a gas at constant volume (i.e. $PV = nRT$), there is manipulation of a variable (temperature). This is an example of manipulative hypothesis testing. In a titration experiment, the pH may be measured when acids and bases are mixed. Here there would be manipulation of the volume of acid/bases that is added but we may not start with a hypothesis. Rather, we may just be interested in noting the quantities involved. This is an example of a manipulative parameter measurement. In a chemical reaction between an acid and a metal, we might hypothesise that a gas will be released. If we simply do the experiment to make an observation about the release of a gas, then we are not changing any variables. We are simply testing a hypothesis about a gas being released, without changing any variables. This is an example of non-manipulative hypothesis testing. In a precipitation reaction, we may simply be interested in observing colours of different precipitates when solutions are

	Manipulate	**Not Manipulate**
Test Hypothesis	Manipulative hypothesis test *e.g. Crookes' study of gases*	Non-manipulative hypothesis test *e.g. De Boisbaudran's discovery of gallium*
Measure Parameter	Manipulative description or measure *e.g. Rutherford's artificial transmutation of elements*	Non-manipulative description or measure *e.g. Mendeleev's prediction of gallium*

Table 2. Brandon's matrix and chemistry examples (from Erduran & Dagher, 2014).

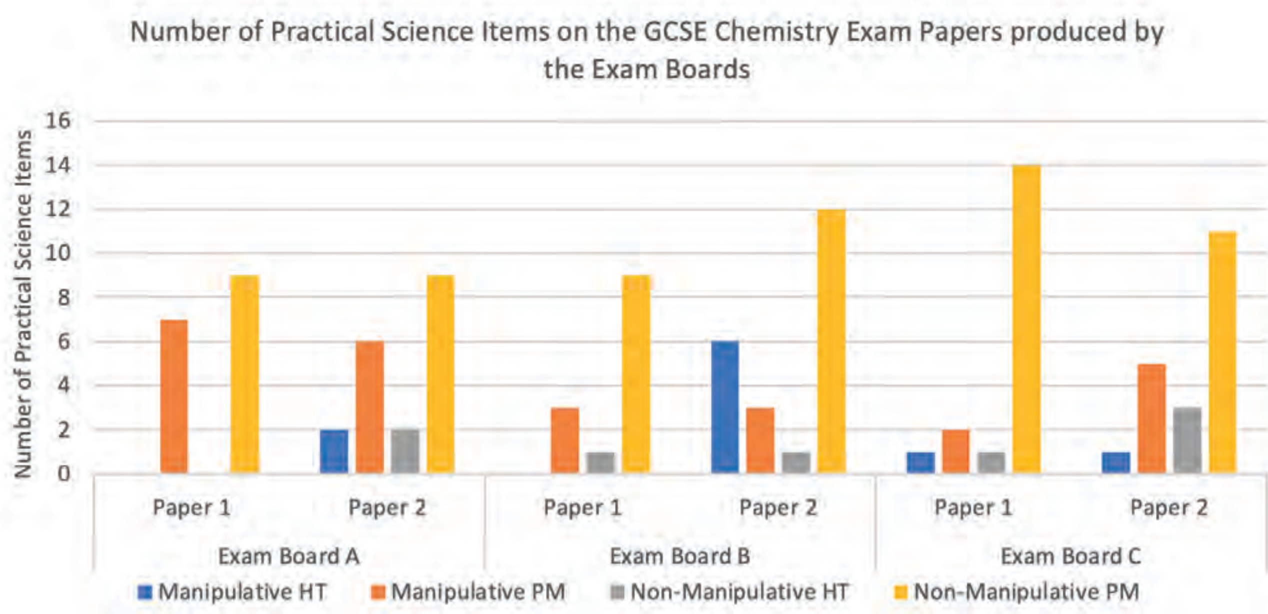

Figure 2. Distribution of items and marks in Exam Papers 1 and 2 across Brandon's Matrix on the three exam boards (from Cullinane, Erduran & Wooding, 2019).

mixed. Here there is no manipulation, simply observation about the parameters (colour change). In this example, there is non-manipulative parameter measurement or observation.

Any of these chemistry topics can be thought with respect to each of the Brandon's categories depending on the approach taken. For example, if we wanted to investigate the rate of hydrogen production relative to the concentration of an acid in a reaction with a metal, different acid concentrations can be viewed as a variable. Such an investigation would have a different purpose than the one previously mentioned, and it would use a different method, namely manipulative hypothesis testing. In Erduran and Wooding (2021), we illustrate how in the context of chromatography, depending on how the investigation is set up, they can belong to each quadrant of the matrix. The important point here is to recognise that there is no single approach to doing an investigation in chemistry. Rather, depending on the goal of the investigation there may be different priorities such as hypothesis testing or simply observation and description. All of these methods are important in chemistry and recognising the different approaches can help us understand why and how we are doing what we are doing in chemistry.

Question 5 [combined task]

Students are investigating water samples.

Student **A** thought that a water sample with pH of 7 was pure.

To find the pH the student added universal indicator solution to a sample of tap water.

Student **B** investigated the boiling point of the water samples.

The student measured the temperature the samples boiled at.

Student **C** compared sea water and bottled water.

The student predicted that sea water contained more impurities than bottled water.

Student **D** tested a sample of bottled water to see which ions were dissolved in the water.

5.1 Which two students are testing a hypothesis? **[1 mark]**

Student ____ and student ____

5.2 Write down the hypothesis that one of these students is investigating. **[1 mark]**

Student ____

Hypothesis:

____

____

5.3 Name one student who did not make a hypothesis.

Is this a scientific investigation?

Circle either "Yes" or "No" below, and then justify your answer. **[3 marks]**

Student_____ Yes / No

Justification:

____

____

____

____

5.4 Make a prediction about the results of student B's experiment with a pure water sample and with an impure water sample.

Draw a line from the type of water sample to the predicted boiled point. **[2 marks]**

Water sample	Boiling Point
	-2 ºC
Impure water	0 ºC
	2 ºC
	98 ºC
Pure water	100 ºC
	102 ºC

5.5 Compare the methods of student **A** and of student **B.**

Which method is likely to be the most accurate in showing is a water sample is pure?

Explain why the method is more accurate. **[3 marks]**

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Figure 3. Project Calibrate Examination Question about Diversity of Methods in Chemistry.

Scientific Methods in High Stakes Examinations

In exploring the relevance of Brandon's Matrix for chemistry education, we have turned to an analysis of questions in high stakes examination questions in England. We have observed that each category of Brandon's Matrix is applicable to examination questions and marking schemes (Cullinane, Erduran & Wooding, 2019). We investigated three English examination boards' examination papers (Figure 2). Papers 1 and 2 assess different content from the curriculum and different exam boards label them differently, but ultimately, the content is consistent with the national curriculum. Paper 1 examines the first five topics from the curriculum (i) the atomic structure and the periodic table; (ii) bonding, structure, and the properties of matter; (iii) quantitative chemistry, (iv) chemical changes; and (v) energy changes. Paper 2 examines (vi) rate and extent of chemical change; (vii) organic chemistry; (viii) chemical analysis, (ix) chemistry of the atmosphere; and (x) using resources and key ideas. Our analysis demonstrated a trend towards more marks being allocated to manipulative type questions. However, there were more items dedicated to non-manipulative parameter measurement as compared to manipulative parameter measurement in the examination questions but not in the marks allocated to the questions.

The pattern suggests consistency between the questions allocated to each category and the marks allocated to them across the examination boards. There is also consistency in the way that the marks are allocated to manipulative type questions, even though the relative frequency for the items were lower. This observation suggests that manipulative type questions are considered to be worthy of more marks and possibly more cognitively demanding. Overall, the analysis of the examination questions and the marks highlight the fact that there is variation in the distribution of different methods of chemistry examination questions in high-stakes tests in England. Teachers tend to structure their teaching towards the examinations that their students will sit. Hence, overemphasis on one method would imply that teachers spend more teaching time preparing their students for such items and less on others, ultimately students having a disproportionate exposure to the diversity of methods in chemistry. How, then, can examination questions be more balanced and representative of the diversity of methods in chemistry? We have addressed this key question in the context of Project Calibrate (2020).

Project Calibrate: Designing Chemistry Assessments using Brandon's Matrix

Project Calibrate is a 3-year project that aimed to incorporate epistemic perspectives on practical science in science education in England (Erduran *et al*, 2020; El Masri, Erduran & Ioannidou, 2021; Erduran & Wooding, 2021; Ioannidou & Erduran, 2021). The project was guided by a systematic approach to considerations of teaching and assessment. The project engaged with examiners from different examination boards to produce assessments. Figure 3 illustrates one example where students are asked to compare and contrast different methods in chemistry.

There are four scenarios involving the investigation of water samples, and the questions target the identification of hypothesis testing. One of the misconceptions about scientific methods is that the scientific method has to include a hypothesis and an experiment (Ioannidou & Erduran, 2021). Hence, one of the questions focused on getting at students' characterization of an investigation as being scientific or not on the basis of testing a hypothesis. Finally, one of the questions ask about justification of the suitability of a method, thus putting students in ways of thinking and reasoning that characterize how chemists approach their analyses. In other words, methods are not a given in chemistry but rather, chemists choose particular methods, and justify them for their suitability to pursue an investigation.

In summary, we have produced assessment resources on scientific methods (Project Calibrate, 2020) and analysed the chemistry examination questions (Cullinane, Erduran & Wooding, 2019) using Brandon's Matrix. In the case of the assessments, Brandon's Matrix guided the design of new questions. In the case of the analysis of existing examination questions, Brandon's Matrix served as an analytical tool. Taken together, the use of the same framework provides consistency and systematicity in approaching educational research and practice, and the overall approach of Project Calibrate illustrates how an epistemic construct such as Brandon's Matrix can serve educational purposes ranging from document analysis to the design of novel educational resources.

Discussion

Our work in Project Calibrate has focused on the case of scientific methods. The use of Brandon's Matrix is intended to highlight to students the importance of diversity of methods in chemistry so that they can place as much value on not only hypothesis testing but also non-manipulative descriptions and measurements. The fact that Brandon's Matrix explicitly highlights in a 2-by-2 table the various methods that can be used in chemistry helps foster a meta-cognitive perspective on what methods are, why they are used and how they relate to different aims in chemical inquiry. When students are immersed in contexts where they compare and contrast as well as justify methods, they are engaged in critical thinking and evaluation. Other dimensions of the epistemic core of chemistry, such as the epistemic aims and values, practices and knowledge can be investigated empirically as well, given the theoretical justification of these aspects have already been made. Ultimately, students' engagement in epistemic aspects of chemistry is likely to foster their appreciation of the nature of chemistry.

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