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The Development and Use of a Pedagogical History for a Key Chemical Idea: the Case of Ions in Solution

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Abstract

A pedagogical history for a chemical idea combines a knowledge of the historical and philosophical background of that idea with what is known about the teaching and learning of that idea and is presented in a format and language that should make sense to a student. The development and use of such a pedagogical history for ions in solution is discussed in this paper. The emphasis is at the upper secondary or lower tertiary level and attempts to illustrate how chemical knowledge is constructed. An understanding of the nature of chemistry is a planned outcome of the exercise.

Introduction

Much has been written about the historical approach to the teaching and learning of chemistry. Schwartz (1977) suggests at least eight important outcomes of an historical emphasis in chemical education: chemistry is not a monolith rising toward omniscience but a subject often full of ambiguity; validation of ideas occurs through experiment, logic, mathematics, and even aesthetics; history dispels the notion of a single universal scientific method but reveals a wide variety of often intensely personal approaches; human diversity of scientists; the role of the imagination in the practice of science; value-laden choices made by practising chemists; social consequences of chemistry; and a revelation of the nature of truth albeit small-t truth. These eight outcomes are components of what Leopold Klopfer (1969) previously called *scientific literacy*. While the goals of scientific literacy are admirable Stephen Brush (1974) cautions us with respect to some of the possible outcomes. For example, young students might find the ambiguity and complexity of the origin of chemical ideas rather daunting and thus the historical approach could in fact rebound on us. However, Brush concludes that if the chemical ideas are introduced sensitively the historical approach could have "a redeeming social significance". That is, a more realistic picture of science demonstrated through its history may reduce the hostility to science bred through an image of the robot-like scientist lacking emotions and moral values. Henry Bent (1977) also speaks about the difficult but desirable features of the historical approach to the teaching of chemistry. He compares the historical approach to the textbook approach and views chemistry in history as "risky, insecure, inductive reasoning, from properties to principles. It uses facts aggressively to capture concepts". On the other hand, chemistry in textbooks is "safe, dependable, deductive reasoning, from principles to properties. It uses facts passively to illustrate ideas".

Chemistry curricula as revealed in textbooks have been criticised for their emphasis on algorithmic problem solving rather than conceptual problem solving (Nakhleh 1993) and Lin (1998) has demonstrated that exposure to history of science cases in chemistry can enhance conceptual problem solving ability. Klopfer (1963) demonstrated that gains in the understanding of science and its processes followed a study of history of science cases by students in US high schools. In spite of these positive research results the use of history in the teaching of science and chemistry in particular has received only limited support. In 1989 the International History and Philosophy of Science and Science Teaching Group (IHPSST) was formed with only limited representation from chemists. In fact, the role of history and philosophy of science in the discipline of physics has received more attention than has its role in the discipline of chemistry. Bent (1977) argues that from a history of science point of view "chemistry is more complicated than physics. A match dropped is physics. A match struck is chemistry. Free fall is easier to describe mathematically than combustion". The importance of showing our students how chemical ideas developed in modern society has, nonetheless, been highlighted on the international stage through such bodies as the IHPSST group and has now been incorporated as a requirement in the NSW Board of Studies chemistry syllabus. One of the reasons for the lack of application of history in chemistry teaching apart from those already mentioned has been the lack of supporting materials for teachers. This paper on a pedagogical history of *Ions in Solution* is illustrative of an attempt to provide such materials for chemical educators at the upper secondary and tertiary level.

What is a pedagogical history?

A pedagogical history differs from the history of science (HOS) cases published by Klopfer (1964) for secondary schools and the Harvard Case histories in experimental science for college and university students (Conant, 1948) in that it includes information relating to the teaching and learning of the particular concept from the research literature. The purpose of developing a pedagogical history for a chemical concept is to show students how a chemical idea was developed from rudimentary information into a substantive concept using important information about alternative conceptions that students have been shown to possess and combining this with important historical and philosophical considerations gleaned from the literature. The history and philosophy is designed to breathe life into what Norman Robert Campbell (1953) called "the dry bones of knowledge from which the breath has departed". The knowledge of alternative conceptions is designed to

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assist students in making a transition from what is often common sense knowledge to scientific knowledge. I would now like to illustrate how a pedagogical history for the topic, Ions in Solution, was developed. The first stage was a historical and philosophical study of the topic.

Ions in Solution-historical and philosophical considerations

A historical and philosophical study of this topic in the context of the teaching and learning of chemistry was published recently (de Berg 2003). The major features of this study which are pertinent to the development of a pedagogical history are:

1. *The study used primary and secondary sources for relevant information*. These sources which date back to the late nineteenth century are invariably written in a style most unsuitable for student use. The techniques used and the experimental data obtained however are important insofar as they are related to concept development. I decided for the purpose of writing a pedagogical history to include only the techniques and data related to conductivity and freezing point depression. There were at least six other techniques I could have used but one has to be careful of information overload in a pedagogical history and I tried to pick properties which I could develop into a storyline that would make sense to students. For example, the property of freezing point depression enables me to talk about relaxing salt baths after a vigorous game of basketball or rugby, the spreading of salt on icy roads in cold climates, and the use of antifreeze for radiators. I selected more than one technique because of the suggested importance of experiment in deciding between competing theories. It is not intended that a pedagogical history be a faithful historical record of all relevant features related to the development of a chemical concept. A pedagogical history has its focus on student learning rather than history of science but selectively uses data from the history of science and pedagogical studies to faithfully represent how a chemical idea was developed. While a pedagogical history will not be comprehensive in its treatment of history it should reflect and respond to the best scholarship in the field in its selectivity.

2. *The topic is a good one for illustrating controversy in chemistry*. The electrolytic dissociation theory for salts in aqueous solution is arguably one of the most controversial in the history of chemistry. Arrhenius, van't Hoff, and Ostwald favoured the "spontaneous dissociation in water" theory while Armstrong, Fitzgerald, and Pickering favoured the "spontaneous association with water" theory. This is an ideal situation for a pedagogical history because it shows how competing theories are treated in the development of chemical ideas. It illustrates how experiment cannot always decide between competing theories and also shows how anomalous data is treated in theory formation. The colourful language used particularly by Henry Armstrong really highlights the controversy and shows how religious insights impacted on Armstrong's attitudes. For example, in reacting to the Xray study of sodium chloride by Professor William Bragg, Armstrong (1927, p478) said, " (This) is repugnant to common sense, absurd to the nth degree, not chemical cricket. Chemistry is neither chess nor geometry whatever Xray physics may be. Such unjustified aspersion of the molecular character of our most necessary condiment must not be allowed any longer to pass unchallenged. A little study of the Apostle Paul may be recommended to Professor Bragg as a necessary preliminary even to Xray work,—, that science is the pursuit of truth. It were time that chemists took charge of chemistry once more and protected neophytes against the worship of false gods: at least taught them to ask for something more than chess-board evidence". It turns out that both theories made contributions to our modern understanding of the dissolution of salts in aqueous solution in spite of the ultimately favoured dissociation theory. The dissociation theory is a good example of a theory that has undergone refinements 'at the edges' over time while the 'hard core' propositions of the theory have remained in place. The colourfulness of this debate lends itself to a dramatic presentation by students or staff.

3. *The role of 'idealisation' and 'mathematisation' in the development of chemical concepts feature in the development of the notion of electrolytic dissociation*. Mathematics did not have an easy passage into chemistry as illustrated by this study. Pickering (1897, p223) reacted to the role of numerical relations in chemical theory by saying, "However convenient such theories (dissociation) may be as working hypotheses their advocates should not have forgotten that they depend solely on the numerical relations alluded to, and that something more than this is required before such hypotheses can be raised to the level of acceptable theories". Armstrong (1928, p51) also questioned the role of numerical relations in chemistry and concluded that, "we have to recover this (chemical feeling) or chemistry will be imperilled".

   In the pedagogical history a reasonable amount of space is given to helping students observe that freezing point depression is proportional to the number of moles of solute and inversely proportional to the mass of solvent by using close to ideal data. The real data from Raoult's study is then presented to the students for their reaction. Reasons for departure from the ideal case are discussed in relation to anomalies in the data. Idealisation of course marks the difference between medieval or Aristotelian science and modern science and featured in Galileo's mathematisation of falling bodies. It features again in the development of the concept of ideal solutions and is an important lever to the emergence of mathematics in chemistry just as it was in physics. A pedagogical history can demonstrate that mathematical equations in science can possess a life of their own despite their common use in algorithmic problem solving.

Ions in solution-teaching and learning considerations

The literature (Ebenezer & Gaskell 1995; Ebenezer & Erickson 1996) on children's understanding of the solution process reveals that children use terms like melting, disintegrating, and dissociating to describe what happens when sugar or salt dissolves in water but nothing is considered different about the way sugar and salt dissolves. Some consider the sugar and salt particles to fit into the air spaces left in the water during dissolving. Research (Taber 2002, p101) has shown that some children think that the solute 'disappears' when dissolved in water and this has at least two interpretations. By 'disappear' some mean that it is actually not present any longer but others mean it is present but not visible. However, some students who believed that the solute was present but not visible thought that the weight of the solution was identical to what it was before the solute was added. They thought the weight increased while there was undissolved solid present but decreased back to the original weight when dissolved. These are important ideas to address when developing the pedagogical history.

Structure of the Pedagogical History Draft 1

The overall structure is that of a storyline with diagrams, data, and questions interspersed with the text. Space is allowed for students to write in their responses to questions. The first draft has been published for trial on the website controlled by Professor Liberato Cadellini: wwwcsi.unian.it/educa/main.html, and consists of ten segments as follows.

1. The pedagogical history begins with a preamble which tries to interface with well recognised events related to the dissolving of solutes in solvents such as salt baths and the salting of roads in cold climates. The dissolving process is modelled taking into account the understandings students reveal according to the research literature.
2. The next section focuses on the dissolving of sugars in water and carefully establishes that the freezing point depression is proportional to the number of moles of sugar dissolved in the water and inversely proportional to the mass of water. At this stage only data from Raoult's original studies that approximates the ideal values are used so that students can be assisted in deducing the mathematical relationships by inspection. Real non-idealised data are introduced later in the pedagogical history. The difference between a molecular lowering factor and a gram lowering factor is introduced to help students see how moles of solute is important in the relationship. The whole idea in this section is to illustrate what is meant by a scientific approach to a problem in terms of isolating variables and controlling them.
3. Having established a relatively constant molecular lowering factor for different sugars the molecular lowering factor for 1:1 salts is introduced. Five 1:1 salts and their molecular lowering factors reported by Raoult are tabulated and the students are challenged to think of a possible explanation as to why the molecular lowering factors are different from the sugars. They are led to consider the magnitude of the numbers as a possible clue.
4. The Arrhenius dissociation model proposed in 1887 is introduced and the students are asked to record what possible objections could be raised against it. Students are also introduced to the objections made by Armstrong, Fitzgerald, and Pickering.
5. Students are introduced to conductivity studies of salt solutions and how the Arrhenius camp used these studies to verify the presence of ions in solution. The Armstrong camp indicated that the ions had been created by the external electricity source and not by the spontaneous dissociation of the salt. The students are asked to indicate whether the conductivity data categorically prove that salts spontaneously dissociate into ions in aqueous solution or whether the data simply supports the notion.
6. Armstrong's 'association with water' hypothesis is introduced to explain the salt data. This hypothesis focuses on the effect of the salt on water whereas the Arrhenius hypothesis focuses on the effect of water on the salt. Armstrong considers that the freezing point depression depends on the number of free hydrone (H_2O) molecules present in the solution. In the case of 1:1 salts two hydrone molecules for every salt molecule are associated with the salt and are no longer free whereas in the case of sugar molecules only one hydrone molecule per sugar molecule is associated. This explained, according to Armstrong, why the molecular lowering factor for 1:1 salts was nearly double that for sugars.
7. Students are asked to consider Raoult's freezing point depression results for calcium chloride and barium chloride and to write down how Arrhenius and Armstrong would have explained the results. They are also asked to indicate how Arrhenius and Armstrong would have explained the fact that a calcium chloride solution conducts electricity.
8. The role of critical experiments which can help one decide between two or more competing models is introduced here. The advent of Xray diffraction is discussed and its role in indicating that the sodium and chlorine species in the solid common salt lattice was Na^+ and Cl^- and not the neutral atoms is highlighted. Armstrong's colourful published reaction to this suggestion is presented to students for their reaction. Armstrong had strong opinions about what techniques were appropriate for chemists and which techniques were inappropriate. This incident highlights the fact that the presentation of counter evidence does not always lead to theory change.
9. In Raoult's original freezing point depression data anomalous results are present and students are asked to identify and respond to these. Some reasons for departure from expected results are given and students asked to select which reasons may account for the anomalies.
10. In summary students are asked to respond to some

questions related to dealing with conflicting models in science, the role of a scientist's personality in theory acceptance or rejection, and the role of evidence and belief in the construction of scientific models.

Student reactions to the first draft

Preliminary trials of the first draft have been completed with eight BSc students studying chemistry as a major, minor, or elective study. The students were asked to complete the pedagogical history in their own time. Some completed the task before formally studying colligative properties and others after having formally studied colligative properties of solutions. Without exception student overall impressions are favourable. One student said, "I never knew this was such a controversial idea. It is great to see how the idea of dissociation developed".

Students found the section on the quantitative treatment of the freezing point depression data particularly helpful in terms of the nature of a scientific investigation. One student said, "This has really helped me to understand the role of definitions and mathematics in chemistry". Some students found the question, "What would the molecular lowering factor have been if Raoult had used 500 grams of water instead of 100 grams?" puzzling while others suggested that the solution would be more dilute and therefore that the molecular lowering factor would drop to one-fifth its value for 100 grams. This suggests that I probably need to establish through some examples that the depression is inversely proportional to the mass of water rather than assume it. The second draft will establish this.

Some students mentioned that they were not able to answer some questions without reading further ahead in the document. For example, determining what can vary in a freezing point depression experiment was not obvious to all students and some indicated that they decided on an answer only after reading the next few paragraphs in the document. This situation is consistent with the research reviewed by Chinn and Brewer (1993,p20-21) which showed that children and adults are deficient in their understanding of such methodological matters as controlled experimentation and the interpretation of covariation information. Perhaps this is why the students found the section on controlled experimentation so helpful. Some students also found it difficult to suggest an objection to Arrhenius' dissociation model without reading further in the pedagogical history. In fact, students have implicitly accepted the presence of separate positive and negative species in solution for so long in their chemical education that they do not think to question why oppositely charged species do not attract and come back together as a unit again. This was a major objection raised by the Armstrong camp. On reading of Armstrong's objection the students always express surprise that they didn't think of the objection themselves.

Students had no difficulty in interpreting the calcium and barium chloride results using both the Arrhenius and Armstrong models and most were able to locate anomalies in Raoult's data and give an explanation for it. Some students were particularly articulate in the way they answered the last three questions regarding conflicting models, the role of a scientist's personality, and the roles of evidence and belief in theory formation. In relation to the question about the role of evidence and beliefs in the construction of scientific knowledge a second year student said, "Beliefs are the views and opinions that scientists bring to their work, while evidence is results or data that support a particular belief. In this article there were two beliefs concerning the dissolving of salt and sugar in water….. Arrhenius' view of dissociation into ions led him to conclude that the conduction of electricity in a salt solution was evidence for dissociation while for Armstrong this was not evidence and he came up with an alternative explanation. Even in the face of strong evidence provided by physics, Armstrong would not give up his belief. Beliefs strongly colour how evidence is interpreted". Students found the pedagogical history easy to read and informative about the way chemical knowledge is developed. I do not think this exercise would have been so helpful to the students if the storyline didn't have appropriate prompts which students could locate in the text. These prompts act as scaffolding (Taber 2002, p73) to support the learners' progress in knowledge acquisition.

Draft 2 of the pedagogical history will contain the changes already suggested as well as other refinements such as in the Xray section. It is important to note that powder Xray diffraction techniques distinguish between K^+ and K for example because it is the electron structure that is responsible for the diffraction and K^+ and K have a different number of electrons. Draft 2 will also contain a development of the equation, $\Delta T_f = ik_f m$, and a enhanced discussion of idealisation and mathematisation in chemistry. This latter addition will suit the tertiary edition of the pedagogical history but not the secondary school edition.

Conclusion

Early indications are that this is a project worth pursuing into further drafts and trials. The use of a pedagogical history in the teaching of chemistry should lead to a situation where assessment items in examinations will require not only typical problem solving activities but a knowledge of how chemical ideas came to be established. The primary purpose of a pedagogical history is not the teaching of history but epistemology as Heilbron (2002) has so adequately described. A greater understanding of how chemistry fits into the great scheme of the history of ideas in our civilisation should result.

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the usefulness of the research activities, most of them indicated to have a lack a clear insight in the underlying goals of the course and the research. The findings were used to revise the module, the 'didactical' scenario, and the design of the teacher course for a next cycle of teaching and inquiry.

In conclusion, the present 'developmental' research is one of the many faces of action research. This paradigm can contribute to the bridging of the research-practice gap, but it is also obvious that a number of potholes should be filled and pitfalls avoided in order to make the bridge an effective way of bringing research and practice together.

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Editorial - The (non) perception of chemistry as human activity

photograph or two. It is worth reading some of the papers of Mansoor Niaz[1] from Venezuela who argues for more authentic exposure to the debates of times gone by in the development of our knowledge.

And also as throw-aways, rather than basic foundations, are the discussion of the cutting edges of chemistry advancement, their intent, their potential usefulness, and their human involvement. Difficult? Biologists manage to present difficult stuff to students by highlighting the key features. Why can't we?

We have been, and are, bound by the use of passive language, and a belief that we need to present chemistry according to an analysis of the logic of the discipline seen from the eyes of the expert chemist. These are not serving us well.

RBB

[1] For example. Niaz, M. and Rodriguez, M. A. (2001) Do we have to introduce history and philosophy of science or is it already 'inside' chemistry? *Chemistry Education: Research and Practice in Europe*, 2(2), 159–164. Available on-line at http://www.uoi.gr/cerp/2001_May/contents.html

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