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HOW TO FACILITATE STUDENTS' CONCEPTUAL UNDERSTANDING OF CHEMISTRY? --- A HISTORY AND PHILOSOPHY OF SCIENCE PERSPECTIVE

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A Framework to Facilitate Conceptual Understanding

A review of the literature shows that the following aspects play an important role in the facilitation of conceptual change:

1. Relationship between the process of theory development by scientists and a students' acquisition of knowledge (Kitchener, 1986; Piaget & Garcia, 1989; Chinn & Brewer, 1993).
2. As a prerequisite for conceptual change it is essential that students be provided with opposing views that contradict their previous knowledge (alternative conceptions) and the two constitute rival theories for students' thinking (Lakatos, 1970).
3. Development of new ideas in science has its origins not in objective facts alone but in a conception, a deliberate construction of the mind --- a heuristic principle (Schwab, 1962; Holton, 1978, Lakatos, 1970).
4. The new/alternative framework must appear initially plausible to the students (Strike & Posner, 1985) in order to facilitate 'progressive transitions' in understanding (Linn & Songer, 1991).
5. Design of interactive 'teaching experiments' to generate situations / experiences in which students are forced to grapple with alternative responses leading to cognitive conflicts (Piaget, 1980; Vygotsky, 1978).
6. Task analysis of students' strategies based on Pascual-Leone's (1987) Theory of Constructive Operators, which facilitates a conceptual and epistemological origin of students' thinking (Niaz, 2002; Niaz & Chacón, 2003; Tsaparlis, 1998).

Conceptual Change Teaching Strategy

Recent research in chemistry education has recognized the importance of conceptual understanding. The objective of this study is to review recent literature in chemistry problem solving and evaluation of chemistry textbooks, to show how it can facilitate conceptual understanding. Despite important advances in chemistry education, teaching students algorithmic strategies still remains the dominant paradigm. To illustrate the difference between student performance on an algorithmic and conceptual problem consider the following problems:

Algorithmic Problem: Given the following standard-state half-cell reduction potentials:

$E^o_{Mn^{2+}, Mn}$ = -1.04 V; $E^o_{Ni^{2+}, Ni}$ = -0.23 V

Calculate the standard-state cell potential based on these half-cells and indicate the direction of the spontaneous reaction.

Conceptual Problem: Eleven grams of a sample of iron ore containing Fe_2O_3 is treated adequately to obtain a solution containing Fe^{3+} (aq). Calculate the purity of Fe_2O_3 in the sample if 29 minutes are required to deposit all the Fe^{3+} (aq) in the solution, with a current of 13 amperes.

These problems formed part of a study to show not only that students perform poorly on conceptual problems but rather to design a teaching strategy that could facilitate students' conceptual understanding. A major premise was that providing students with the correct response along with alternative responses (teaching experiments) provides a rival/conflicting situation (Lakatos, 1970) that is conducive towards an equilibration of their cognitive structures (Piaget, 1985). Results obtained showed that 70% of the students in the experimental group and 66% in the control group solved the algorithmic problem correctly. However, performance of both groups decreased considerably on the conceptual problem: 30% for the experimental and 34% for the control group. At this stage the experimental group students participated in two 'teaching experiments'. Results obtained from a posttest showed that 36% of the experimental group students responded correctly, in contrast to 6% of the control group (difference in performance being statistically significant, $\chi^2 = 7.97$, $p < 0.01$).

General Chemistry Textbooks: Do they Facilitate Conceptual Understanding?

Thomson's Cathode Ray Experiments

Most textbooks present J.J. Thomson's cathode ray experiments by emphasizing experimental details at the expense of conceptual understanding, i.e., what was Thomson trying to do, in other words the experiment was a means to an end and not an end in itself, as most textbooks suggest. Was Thomson simply interested in obtaining an accurate value of the mass-to-charge ratio of cathode rays? Of the 23 fairly well-known textbooks analyzed (Niaz, 1998), only two made a simple mention of the fact that Thomson's experiments were conducted against the backdrop of a conflicting framework --- cathode rays could have been charged particles or waves in the ether. Again, only two textbooks described satisfactorily that Thomson determined mass-to-charge ratio in order to decide whether cathode rays were ions or universal charged particles. Thomson (1897) in his seminal article discusses these issues with considerable detail. Most teachers and textbooks do not consult original work. No wonder students do not understand what was Thomson up to and end up memorizing the experimental details found in textbooks.

Alpha Particle Experiment: Thomson-Rutherford Controversy

In order to maintain his model of the atom and explain large angle deflections of alpha particles, J.J. Thomson had put forward the hypothesis of compound scattering (multitude of small scattering). On other hand, E. Rutherford (1911) explained the same experimental data by the hypothesis of single scattering. The two hypotheses based on the same experimental results led to two entirely different atomic models and to a bitter dispute between Thomson and Rutherford that lasted for many years. Of the 23 textbooks (all published in U.S.A.) analyzed none described the Thomson-Rutherford controversy and the fact that experimental data often lead to more than one model / interpretation (Niaz, 1998).

Bohr's Objective: Stability of Rutherford Atom vs. Hydrogen Line Spectrum

Bohr's main objective was to explain the paradoxical stability of the Rutherford model of the atom, which constituted a rival framework for his own model. Historical evidence (Heilbron & Kuhn, 1969) shows that Bohr had not even heard of the Balmer and Paschen formulae for the hydrogen line spectrum, when he wrote the first version of his 1913 article, in the *Philosophical Magazine.* Of the 23 textbooks analyzed none mentioned this important aspect of Bohr's Research Program (Niaz, 1998). Presentation of most textbooks approximated to a 'Baconian Inductive Ascent' (Lakatos, 1970):

Accumulation of data of spectra of elements → An empirical law (Balmer) 1885 → Bohr's (1913) theoretical explanation. A major premise of historians (and textbooks) who follow the 'Baconian Inductive Ascent' is that scientific theories are primarily driven by experimental observations.

The Oil Drop Experiment: Millikan-Ehrenhaft Controversy

R.A. Millikan and F. Ehrenhaft obtained very similar experimental results and still Millikan was led to postulate the 'electron' and Ehrenhaft to 'sub-electrons' (Holton, 1978). Rivalry between the two proponents led to a bitter dispute that lasted for many years (1910-25). Of the 31 textbooks (all published in U.S.A) analyzed none mentioned the controversy (Niaz, 2000a). Most textbooks consider the experiment to be 'simple', 'classic', and 'precise'. Millikan is considered to be a genius who determined the charge of the electron by a 'beautiful' experiment (Niaz, 2005)

Inconsistent Nature of Maxwell's Kinetic Theory of Gases

J.C. Maxwell's theory was based on 'strict mechanical principles' derived from Newtonian mechanics and yet at least two of Maxwell's simplifying assumptions (movement of particles and consequent generation of pressure) were in contradiction with Newton's hypothesis explaining the gas laws based on repulsive forces. Of the 22 (all published in U.S.A) textbooks analyzed none described the inconsistent nature of Maxwell's presentation of the kinetic theory (Niaz, 2000b).

Origin of the Covalent Bond

A reconstruction shows that sharing of electrons had to compete with the transfer of electrons (ionic bond), considered to be the dominant paradigm until about 1920. Formation of the ionic bond leads to a lowering of energy (stabilization) because of electrostatic attraction between ions of opposite charge. How can we explain the lowering of energy when two electrons are shared to form a covalent bond?
Apparently, the approach of two electrons having the same charge should produce repulsive forces and hence destabilization. Thus it is not surprising that when first proposed the idea of a covalent bond was considered to be 'absurd' and 'bizarre'. Lewis (1916) was the first to support covalent bonding by postulating a model based on the cubic atom. J.J. Thomson opposed the covalent bond and considered that all bonds were ionic. Discussion of the origin of covalent bond, based on its rivalry with the ionic bond can facilitate conceptual understanding. Of the 27 textbooks (all published in U.S.A) analyzed only one made a simple mention that sharing of electrons (covalent bond) had to compete with the transfer of electrons, viz., ionic bond (Niaz, 2001).

Explanation of Periodicity in the Periodic Table

Many students must have wondered as to how a simple arrangement of the elements could provide such regularities in the periodic table. Textbooks could promote students' curiosity, interest and conceptual understanding. A historical reconstruction provides an opportunity to facilitate this objective by emphasizing periodicity as a function of the atomic theory. Most textbooks not only ignore the role of atomic theory in the development of the periodic table, but on the contrary emphasize that it was an inductive generalization. Of the 57 textbooks (all published in the U.S.A) analyzed 43 simply ignored the issue and 14 made a simple mention to the role played by the atomic theory (Brito et al. 2005; Niaz et al. 2004)).

Conclusion

- Conceptual change teaching strategies can promote students' interest, curiosity and understanding by showing that science is an human enterprise.
- Teachers and textbooks can endeavor to facilitate the understanding that scientific progress requires going beyond the regurgitation of experimental details.
- History and philosophy of science is 'inside' chemistry provided we are willing to share with our students experiences that reflect the very nature of science: a) Scientific progress is characterized by controversies, conflicts and competition among rival theories; b) Theory ladenness of observations; c) Same experimental data can be interpreted by more than one theory / model; d) Scientific theories are tentative; e) Scientific theories can be based on inconsistent foundations and still continue to progress; f) Empirical data is not the ultimate 'arbiter' in the refutation / acceptance of scientific theories.

References (selected)

Bohr, N. (1913). On the constitution of atoms and molecules. *Philosophical Magazine, 26,* 1-25.

Brito, A., Rodríguez, M., & Niaz, M. (2005). A reconstruction of development of the periodic table based on history and philosophy of science and its implications for general chemistry textbooks. *Journal of Research in Science Teaching, 42*, 84-111.

Chinn, C.A., & Brewer, W.F. (1993). The role of anomalous data in knowledge acquisition: A theoretical framework and implications for science instruction. *Review of Educational Research, 63*, 1-49.

Heilbron, J.L., & Kuhn, T. (1969). The genesis of the Bohr atom. *Historical Studies in the Physical Sciences, 1*, 211-219.

Holton, G. (1978). Subelectrons, presuppositions and the Millikan-Ehrenhaft dispute. *Historical Studies in the Physical Sciences, 9*, 161-224.

Kitchener, R.F. (1986). *Piaget's theory of knowledge: Genetic epistemology and scientific reason.* New Haven: Yale University Press.

Lakatos, I. (1970). Falsification and the methodology of scientific research programmes. In I. Lakatos & A. Musgrave (Eds.), *Criticism and the growth of knowledge* (pp. 91-195). Cambridge: Cambridge University Press.

Lewis, G.N. (1916). The atom and the molecule. *Journal of American Chemical Society, 38*, 762-785.

Niaz, M. (1998). From cathode rays to alpha particles to quantum of action: A rational reconstruction of structure of the atom and its implications for chemistry textbooks. *Science Education, 82,* 527-552.

Niaz, M. (2000a). A rational reconstruction of the Millikan-Ehrenhaft controversy and its implications for chemistry textbooks. *Journal of Research in Science Teaching, 37,* 480-508.

Niaz, M. (2000b). A rational reconstruction of the kinetic molecular theory of gases based on history and philosophy of science and its implications for chemistry textbooks. *Instructional Science, 28*, 23-50.

Niaz, M. (2001). A rational reconstruction of the origin of the covalent bond and its implications for general chemistry textbooks. *International Journal of Science Education, 23,* 623-641.

Niaz, M. (2005). An appraisal of the controversial nature of the oil drop experiment: Is closure possible? *British Journal for the Philosophy of Science, 55*, (in press).

Niaz, M., Rodríguez, M., & Brito, A. (2004). An appraisal of Mendeleev's contribution to the development of the periodic table. *Studies in History and Philosophy of Science, 35*, 271-282.

Pascual-Leone, J. (1987). Organismic proceses for neo-Piagetian theories: A dialectical causal account of cognitive development. *International Journal of Psychology*, *22*, 531-570.

Piaget, J., & Garcia, R. (1989). *Psychogenesis and the history of science*. New York: Columbia University Press.

Rutherford, E. (1911). The scattering of alpha and beta particles by matter and the structure of the atom. *Philosophical Magazine, 21*, 669-688.

Schwab, J.J. (1962). *The teaching of science as enquiry*. Cambridge, MA: Harvard University Press.

Thomson, J.J. (1897). Cathode rays. *Philosophical Magazine*, *44*, 293-316.

Tsaparlis, G. (1998). Dimensional analysis and predictive models in problem solving. *International Journal of Science Education*, *20*, 335-350.