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AUTHOR	Niaz, Mansoor
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ABSTRACT

The main objective of this study is to construct models based on strategies students use to solve chemistry problems and to show that these models form sequences of progressive transitions similar to what Lakatos (1970) in the history of science refers to as progressive 'problemshifts' that increase the explanatory' heuristic power of the models. Results obtained show the considerable difference in student performance on chemistry problems that require algorithmic or conceptual understanding. The difference between student performance on algorithmic and conceptual problems can be interpreted as a process of progressive transitions (models) that facilitate different degrees of explanatory power to student conceptual understanding. A parallel is drawn between the methodology of idealization (simplifying assumptions) used by scientists and the construction of strategies (models) used by students to facilitate conceptual understanding. A major educational implication of this study is that the relationship between algorithmic and conceptual problems is not dichotomous but rather characterized by a continuum that consists of sequences of models that facilitate greater conceptual understanding. This reconstruction of student strategies to solve problems (progressive transitions) can provide the teacher a framework to anticipate as to how student understanding could develop from being entirely algorithmic to conceptual. (Author)

PROGRESSIVE TRANSITIONS FROM ALGORITHMIC TO CONCEPTUAL UNDERSTANDING IN STUDENT ABILITY TO SOLVE CHEMISTRY PROBLEMS: A LAKATOSIAN INTERPRETATION

MANSOOR NIAZ

Chemistry Department, Universidad de Oriente

Apartado Postal 90, Cumaná, Estado Sucre, Venezuela

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ABSTRACT

The main objective of this study is to construct models based on strategies students use to solve chemistry problems and to show that these models form sequences of progressive transitions similar to what Lakatos (1970) in the history of science refers to as progressive 'problemshifts' that increase the explanatory / heuristic power of the models. Results obtained show the considerable difference in student performance on chemistry problems (mol, gases, solutions, and photoelectric effect) that require algorithmic or conceptual understanding. The difference between student performance on algorithmic and conceptual problems can be interpreted as a process of progressive transitions (models) that facilitate different degrees of explanatory power to student conceptual understanding. A parallel is drawn between the methodology of idealization (simplifying assumptions) used by scientists and the construction of strategies (models) used by students to facilitate conceptual understanding. A major educational implication of this study is that the relationship between algorithmic and conceptual problems is not dichotomous but rather characterized by a continuum that consists of sequences of models that facilitate greater conceptual understanding. This reconstruction of student strategies to solve problems (progressive transitions) can provide the teacher a framework to anticipate as to how student understanding could develop from being entirely algorithmic to conceptual.

DIFFERENCE BETWEEN ALGORITHMIC AND CONCEPTUAL PROBLEMS

Most high school and freshman general chemistry courses emphasize the application of algorithms to solve routine (plug-and-chug) problems (Nurrenbern & Pickering, 1987). It appears that for most teachers solving numerical problems that require algorithmic solution strategies in contrast to conceptual understanding, is a major behavioral objective of freshman chemistry. According to Sawrey (1990): "Many instructors, myself included, have believed (or hoped) that teaching students to solve problems is equivalent to teaching the concepts. If, as is now being proposed, the axiom is not true, then we all must rethink our approach to chemical education" (p. 253). What, however, makes the problem more difficult is the fact that this has been an, "... unquestioned axiom of freshman chemistry teaching for the last 30 years" (Pickering, 1990, p. 254). Furthermore, text-books generally do not emphasize conceptual understanding. According to De Berg (1989): "... if text-books are a guide to what students learn in classroom, it is no wonder that the 'algorithmic' mode of problem solving in gas law problems predominates ..." (p. 119). More recently, Chiappetta, Sethna, and Fillman (1991) have shown that high school chemistry text-books not only deemphasize science as a way of thinking, but also do not stress the importance of how chemists discover ideas and experiment, historical development of chemistry concepts, cause-effect relationships, and self-examination of one's thinking in the pursuit of knowledge.

A review of the literature shows that many students solve chemistry problems using algorithmic strategies and do not understand the chemical concepts on which the problems are based (cf. Abraham, Grzybowski, Renner, & Marek, 1992; Ben-Zvi, Eylon, & Silbersten, 1986; BouJaoude, 1992; Gabel, Sherwood, & Enochs, 1984; Garnett & Treagust, 1992; Griffiths & Preston, 1992; Haidar & Abraham, 1991; Hesse & Anderson, 1992; Linn & Songer, 1991; Mitchell & Kellington (1982); Niaz & Robinson (1992, 1993); Novick & Nussbaum (1978); Schmidt, 1992).

In spite of the increasing awareness among science educators of the difference between algorithmic and conceptual problems, more work needs to be done on the psychological (cognitive variables) and epistemological basis of this difference. Niaz & Robinson (1993), for example, have shown that for chemistry problems requiring algorithmic strategies (computational problems), formal operational reasoning is an important predictor of performance. On the other hand, for problems requiring conceptual understanding (based on a figurative format), variance in performance is explained by different cognitive variables such as, information processing (Pascual-Leone, 1970, 1987), cognitive style (Witkin & Goodenough, 1981), and formal operational reasoning (Inhelder & Piaget, 1958). An important finding of this study is that ability to solve algorithmic (computational) problems is not the major factor in predicting success in problems that require conceptual understanding. This finding provides empirical support against one of the "... unquestioned axiom(s) of freshman chemistry teaching

... " (Pickering, 1990, p. 254), viz., solving routine algorithmic problems leads to conceptual understanding. Haidar and Abraham (1991) have reported that students' preexisting knowledge and formal operational reasoning are associated with their conceptions and use of particulate theory. Garnett and Treagust (1992) have shown that students experience difficulty in understanding oxidation-reduction equations when more than one model (e.g., oxidation conceptualized as gain of oxygen / loss of hydrogen / loss of electrons) is used to explain scientific phenomena. Niaz and Robinson (1992) have studied student performance on two types of gas problems: a) problems requiring enumeration and manipulation of different variables (pressure, volume, etc.) of the Ideal Gas Law, characterized by the 'algorithmic mode'; and b) problems requiring the use of the Ideal Gas Law, which derives its meaning from the kinetic-molecular theory of Maxwell and Boltzmann (a hypothetico-deductive system), characterized by 'conceptual gestalt'. Results obtained led the author(s) to conclude: "... for physical theories in general and for the Ideal Gas Law in particular, one should not expect training or experience with algorithmic problems to develop the understanding required to solve conceptual problems" (Niaz & Robinson, 1992, p. 63). According to Hanson (1958), in spite of the differences between the algorithmic and the conceptual approaches, the two are compatible: "A law might have been arrived at by enumerating particulars; it could then be built into an H-D (hypothetico-deductive) system as a higher order proposition" (p. 70).

A LAKATOSIAN FRAMEWORK FOR UNDERSTANDING THE DIFFERENCE BETWEEN ALGORITHMIC AND CONCEPTUAL PROBLEMS

Lakatos' philosophy of science has been applied previously to interpret research in science education (Gilbert & Swift, 1985; Linn & Songer, 1991; Niaz, 1993a). Space limitations do not permit an elaboration of Lakatos' methodology here and so the reader is referred to the original sources (Lakatos, 1970, 1971, 1974, & 1976).

Following Galileo's method of idealization, scientific laws being epistemological constructions do not describe the behavior of actual bodies. "The gas laws, inheritance laws, Newton's laws, Piagetian stages, etc. --- all of these describe the behavior of ideal bodies, they are abstractions from the evidence of experience. The laws are true only when a considerable number of disturbing factors (itemised in the caeteris paribus clauses) are eliminated ... The art of experimentation is to progressively try to do so" (Matthews, 1987, p. 295). The process of building models, that is, idealization is an important characteristic of modern non-Aristotelian science and has been emphasized by Piaget (1970): "The whole history of physics is about decentration, which reduced to a minimum the deformations introduced by an egocentric subject and based this science to a maximum on the laws of an epistemic subject" (p. 16). The role of the epistemic subject is an important aspect of Piaget's genetic epistemology and Niaz (1991a) has shown its importance for science education.

With this background it is instructive to compare Lakatos' (1970, p. 146) rational reconstruction of Bohr's research program. Lakatos shows how Bohr used the methdology of idealization (i.e., simplifying assumptions) and developed the 'positive heuristic' of his program by progressing from simple to complex models, that is, from a fixed proton-nucleus in a circular orbit, to elliptical orbits, to removal of restrictions (fixed nucleus and fixed plane), to inclusion of spin of the electron, and so on till the program could ultimately be extended to complicated atoms and molecules. Similarly, Lakatos (1970, pp. 135-136) considers Newton's gravitational theory as a research program based on a sequence of evolving models (degree of idealization) that finally led Newton to incorporate interplanetary forces, perturbations, bulging planets rather than round planets, etc. Another example of idealization familiar to science educators is Piaget's genetic epistemology (Kitchener, 1986; Vuyk, 1981). Piaget's problem was much more difficult and thus he focussed on: How is the development of knowledge (competence) possible in an ideal epistemic subject by ignoring variables, such as, "... cognitive styles, studies of variables that detract from correct reasoning, and memory limitations" (Kitchener, 1986, p. 28). In a sense Piaget by studying the epistemic subject followed the Lakatosian methodology (interestingly, even before Lakatos came on the scene). There is of course no limit to the number of variables that can affect performance of the real subjects. In this respect Pascual-Leone's (1970, 1987) theory of constructive operators has played a crucial role in the integration of these variables to Piaget's epistemological framework (cf. Eylon & Linn, 1988; Niaz, 1993b for a critical appraisal). More recently, Niaz (1992) has demonstrated a progressive 'problemshift' in the Lakatosian sense between Piaget's epistemic subject and Pascual-Leone's metasubject, which leads to the development of a theory with greater explanatory power. Similarly, Kitchener (1987) considers Piaget's genetic epistemology as a philosophy of science and that, "... Piaget attempts to explain the growth of knowledge in ways similar to those of Popper and Lakatos, namely, as being a rational reconstruction of the course of epistemic change in which epistemic transitions occur by virtue of certain normative principles" (p. 365).

The above reconstruction from the history of science shows that if scientists adopt the methodology of idealization (simplifying assumptions) in order to solve complex problems, it is plausible to hypothesize that students adopt similar strategies in order to facilitate conceptual understanding. The relationship between the process of theory development by scientists and an individual's acquisition of knowledge has been recognized by philosophers of science and psychologists (Duschl & Gitomer, 1991; Karmiloff-Smith & Inhelder, 1976; Kitchener, 1986, 1987; Piaget & Garcia, 1991). According to Kitchener (1988), Piaget and Garcia, "... provide empirical evidence for the claim that there are, after all, surprising commonalities between psychogenesis and the history of science" (p. 163). It can be further hypothesized that as scientists build models of increasing complexity, which lead to epistemic transitions (i.e., increase heuristic/explanatory power, cf. Lakatos, 1970, p. 137), similarly students build a series of evolving models (progressive transitions) that increase in conceptual understanding. Linn and Songer (1991) have summarized this transition in the following terms: "Essentially, students could base their first prediction on conceptions they brought to science class but would construct their second prediction by integrating the results of their first experiment. Thus students would use observation and prediction as a key component of their student reports to engage in a progrssing research program as described by Lakatos (1970, 1976)" (p. 904).

PURPOSE

The main objective of this study is to construct models based on strategies students use to solve chemistry problems and to show that these models form sequences of progressive transitions similar to what Lakatos (1970) in the history of science refers to as progressive 'problemshifts' that increase the explanatory/heuristic power of the models. Furthermore, to show that the sequences of evolving models generally consist of progressive transitions that vary in the degree to which students manifest algorithmic or conceptual understanding.

METHOD

Eighty three freshmen students (Ss) enrolled in two sections of Chemistry I for science majors at the Universidad de Oriente, Venezuela, participated in the study (mean age = 18.4 years; SD = 1.1; women = 32, men 51). Both sections were taught by the author. Instead of the traditional expository a participatory approach to instruction was used. Ss were encouraged to question and often called to the chalk-board to solve problems. Ss were asked to solve sets of problems that are referred to as experiments in this study. All problems formed part of the regular monthly exams presented by the Ss, and they were encouraged and given credit for justifying as to why they selected a particular response or used a calculation. Ss were presented the problems on all exams in a certain order but they were not obliged to solve them in the same order. The first exam (5th week) was presented by 83 Ss, the second exam (9th week) by 60 Ss and the third exam (12th week) by 44 Ss. In most Venezuelan universities Ss at the freshman level tend to to change careers or drop-out due to poor performance. The number of Ss who presented the three exams in this study were about equally represented by the two sections.

<u>Experiment 1</u>

Ss were asked to solve Items 1A and 1B during the 5th week of the semester. Both items were presented one after the other on the exam, in the following order:

Item 1A

Calculate the moles of the following quantities of nitrogen:

a) 70 molecules b) $56X10^{23}$ atoms

Item 1B

How many moles of the atoms of B (Boron) are present in a sample having $2X10^{23}$ molecules of B_4H_{10}?

a) 1.3 moles b) 4.0 moles

c) 8.0 moles d) None of the previous

Item 1B requires conceptual understanding, whereas Item 1A can be solved by the use of algorithms.

Experiment 2

Ss were asked to solve Items 2A and 2B during the 9th week of the semester. Both items were presented one after the other in the following order:

Item 2A

A certain amount of gas occupies a volume (V_1) at a pressure of 0.60 atm. If the temperature is maintained constant and the pressure is decreased to 0.20 atm, the new volume (V_2) of the gas would be:

a) $V_2 = V_1/6$ b) $V_2 = 0.33\ V_1$

c) $V_2 = V_1/3$ d) $V_2 = 3\ V_1$

Item 2B

An ideal gas at a pressure of 650 mmHg occupied a bulb of unknown volume. A certain amount of the gas was withdrawn and found to occupy 1.52 mL at 1 atm pressure. The pressure of the gas remaining in the bulb was 600 mmHg. Assuming that all measurements were made at the same temperature, calculate the volume of the bulb.

Item 2B was adapted from Mahan (1968) and requires conceptual understanding, whereas Item 2A was adapted from Niaz (1989) and requires an algorithmic strategy.

Experiment 3

Ss were asked to solve Items 3A, 3B, 3C, and 3D during the 9th week of the semester. All 4 items were presented one after the other in the following order:

Item 3A

20 g of Na_2SO_4 were dissolved in sufficient water to obtain 500 mL of a solution with a density of 1.11 g/mL. Calculate the molarity and molality of the solution.

Items 3B, 3C, 3D

Density of a 2.1 M solution of H_2SO_4 is 1.38 g/mL. If 450 mL of water are added to a vessel that contains 850 mL of 2.1 M H_2SO_4, which of the following statements are correct:

Item 3B: The concentration of the final solution would be 2.2 M.

Item 3C: Number of moles of H_2SO_4 in the vessel after the addition of water are the same as before the addition of water.

Item 3D: The original solution of H_2SO_4 is 1.2 molal.

Item 3C requires conceptual understanding, whereas Items 3A, 3B, and 3D can be solved by the use of algorithms. Item 3A was adapted from Niaz (1989). Ss were given the following explicit instructions with respect to Items 3B, 3C, and 3D: (i) More than one of the three statements could be correct. According to Karplus (1979) the inclusion of such an instruction increases the cognitive complexity of the task; and (ii) In order to respond to Items 3B and 3D they must justify their response by a numerical calculation.

Experiment 4

Ss were asked to solve Items 4A, 4B, and 4C during the 12th week of the semester. All 3 items were presented one after the other in the following order:

Item 4A

Calculate the wave length in Angstrom of an electron transition in the spectrum of hydrogen, from n = 4 to n = 2. (Note: Ss were provided values of the constants and the relevant formula in terms of the wave number).

Item 4B

Which of the following statements about the photoelectric effect are correct: a) The surface of a metal does not emit electrons, until the frequency of the impinging light is greater than the threshold value; b) Above the threshold frequency, greater the intensity of light lesser is the velocity of the emitted electrons; c) Above the threshold frequencey, greater the wave length of light greater is the velocity of the emitted electron; d) Above the threshold frequency, lesser the intensity of light greater is the number of electrons emitted per second. (Note: Ss were asked to justify all responses, whether correct or incorrect).

Item 4C

A metal having a threshold wave length of 5900 Angstrom is irradiated with light having a wave length of 3500 Angstrom.

a) Would there be emission of electrons.

b) If electrons are emitted calculate their velocity.

(Note: Ss were provided with values of all the constants)

Item 4B requires conceptual understanding. Items 4A and 4C were adapted from Oxtoby, Nachtrieb, and Freeman (1990) and can be solved by the use of algorithms.

A conceptual item in this study generally represents considerable difficulty for the Ss, as it cannot be solved by memorized algorithms or formulae. This is particularly true of Items 1B, 2B, 3C, and 4B. An algorithmic item in this study is based on mathematical transformations, requiring algorithms and formulae. Although, at least 50% of the class time was allocated to solving and emphasizing conceptual problems, most Ss felt more comfortable in solving algorithmic problems. It is argued that the degree to which a problem is classfied as algorithmic or conceptual is a function of the Ss background and the sort of problems they are exposed to in class. It is possible that Ss with a different background may not consider items used in this study as requiring algorithmic or conceptual understanding. Finally, in spite of the differences between the two types of problems, the relationship between the two is by no means dichotomous.

RESULTS AND DISCUSSION

Experiment 1

It was observed that Ss who solved conceptual Item 1B correctly used one of the following strategies:

Strategy A (two-step solution)

Step 1: $6.023X10^{23}$ molecules ----> 1 mol of B_4H_{10}

$2.0X10^{23}$ molecules ----> X = 0.33 mol of B_4H_{10}

Step 2: 1 mol of B_4H_{10} has ----> 4 moles of B

0.33 moles of B_4H_{10} ----> X = 1.3 moles of B

Strategy B (one-step solution)

$6.023X10^{23}$ molecules of B_4H_{10} have ---> 4 moles of B

$2.0X10^{23}$ molecules of B_4H_{10} have ---> X = 1.3 moles of B

Insert Table 1 about here

It is interesting to observe that out of the 18 Ss (see Table 1) who solved Item 1B correctly, 7 used Strategy B (one-step solution) and 11 used Strategy A (two-step solution). It was further observed that all 13 Ss who got Item 1B partially correct used Step 1 of Strategy A and missed Step 2. Table 1 also shows the considerable difference in Ss performance on the algorithmic Item 1A and the conceptual Item 1B. It was also observed that out of the 47 Ss who solved the algorithmic Item 1A correctly, 12 (26%) solved the conceptual Item 1B correctly, 8 (17%) partially correct, and 27 (57%) incorrectly. On the other hand, out of the 18 Ss who solved the conceptual Item 1B correctly, 12 (67%) solved the algorithmic Item 1A correctly and 6 (33%) partially correct. These results suggest that Ss progressively construct models (based on strategies) that require greater conceptual understanding. Furthermore, it can be argued that Ss using Strategy B are capable of 'chunking' information (cf. Herron, 1988; Niaz, 1989; White, 1988), that is, process information more efficiently. In other words what may be held as separate bits of information to begin with, later with greater expertise and conceptual understanding may be 'chunked' as a single larger unit of information. This suggests the importance of information processing in student reasoning processes (cf. Niaz, 1991b; Pascual-Leone, 1970).

Based on Ss strategies used in solving Items 1A and 1B it is plausible to suggest that they go through a process of progressive transitions and build models that facilitate different degrees of conceptual understanding, quite similar to what Lakatos (1970) has referred to as progressive 'problemshifts'.

<u>Progressive transitions (models) leading to greater conceptual understanding of the mol concept</u>

Model 1: Strategies used to solve Item 1A partially correct (N = 25).

Model 2: Strategies used to solve Item 1A correctly (N = 47).

Model 3: Strategies used to solve Item 1B partially correct, that is, Step 1 of Strategy A (N = 13).

Model 4: Strategies used to solve Item 1B correctly, using the two-step Strategy A (N = 11).

Model 5: Strategies used to solve Item 1B correctly, using the one-step Strategy B (N = 7).

Experiment 2

Results obtained show that 52 Ss solved the algorithmic Item 2A correctly and 8 could not solve it. On the other hand, only 4 Ss solved the conceptual Item 2B correctly, 13 Ss solved it partially correct and 43 Ss could not solve it. This shows the considerable difference in Ss performance on the algorithmic Item 2A and the conceptual Item 2B. All 4 Ss who solved the conceptual Item 2B correctly also solved the algorithmic Item 2A. The 13 Ss who got partial credit for Item 2B, correctly identified the final pressure (1 atm) and the final volume (1.52 mL). These Ss, however, could not conceptualize the initial pressure to be 50 mmHg, and instead used either 600 mmHg or 650 mmHg. This lack of conceptualization clearly shows, how Ss simply memorize the scientific laws (Boyle's law in this case) and the corresponding mathematical equation and look for values to plug in. This is particularly true of another group of 16 Ss who got no credit as they could correctly identify only the final volume (1.52 mL) and used 650 mmHg as the initial pressure and 600 mmHg as the final pressure. Apparently, these Ss had even more difficulty in conceptualizing that 650 mmHg was the initial pressure of the gas in the bulb but not the pressure of the gas that was withdrawn. Furthermore, these Ss could not conceptualize that 600 mmHg was the pressure of the gas that remained in the bulb, whereas the gas that was withdrawn had a pressure of 1 atm. Given the close relationship between the basic skills (Boyle's law) required to solve both Items 2A and 2B, it is surprising that out of the 52 Ss who solved the algorithmic Item 2A, only 4 could solve the conceptual Item 2B. This result provides an opportunity to reflect over the usefulness of spending much class time over such algorithmic problems.

Progressive transitions (models) leading to greater conceptual understanding of gases

Model 1: Strategies used to solve Item 2A correctly, that is, ability to manipulate the three variables of the Boyle's law equation ($P_1V_1 = P_2V_2$) to calculate the fourth (N = 52).

Model 2: Strategies used to correctly identify the final volume in Item 2B, that is, partial conceptualization of the property of a gas when it is withdrawn from a vessel (N = 16).

Model 3: Strategies used to correctly identify and conceptualize two properties of a gas (final volume and pressure in Item 2B), when it is withdrawn from a vessel (N = 13).

Model 4: Strategies used to correctly identify and conceptualize all the variables of a gas (Item 2B) when it is withdrawn from a vessel (N = 4).

Experiment 3

Table 2 shows that in this experiment even the algorithmic problems posed a considerable difficulty for the Ss. For example, Item 3A was solved correctly by 25% (15 out of 60) of the Ss and 42% (25 out of 60) could not solve it. These results are interesting as in this case the Ss did not have the advantage of an algorithmic 'prop' although the problem itself is based on routine procedures well rehearsed in class. Most Ss in Venezuelan high schools are used to solving the concentration problems (molarity, molality, etc.) with formulae. These Ss face considerable difficulty on arrival at the University, where reasoning processes are generally emphasized more than routine algorithmic procedures. It is interesting to observe that in both Experiments 1 and 2, the algorithmic Items 1A (mol formula) and 2A (pV formula) were solved by formulae, which most science educators would consider as appropriate. On the other hand, Ss were specifically told not to calculate concentrations of the solutions with formulae, but instead demonstrate the different steps that lead to the correct answer. Most science educators would accept this as an appropriate procedure. These results show that without the aid of an algorithmic 'prop' Ss performance decreases considerably even on algorithmic problems. Table 2 further shows

Insert Table 2 about here

that out of the 15 Ss who correctly solved the algorithmic Item 3A only 8 could solve another algoritmic Item 3B based on the concept of dilution, and 6 solved conceptual Item 3C. Interestingly, out of the 15 Ss who had correctly calculated the molality in Item 3A, 9 could not do so in Item 3D, presumably due to the context (dilution) in which the problem is presented. The following observations show that the context of dilution was a source of considerable difficulty for the Ss and this affected their performance:

- Some of the Ss calculated the molarity of the final solution (Item 3B) to be greater than that of the original solution (2.1 M) --- evidently ignoring the fact that this problem involved dilution. These Ss reasoned along the following lines:

  "1000 mL of solution have ----> 2.1 moles of H_2SO_4
  850 mL of solution have ----> X = 1.785 moles of H_2SO_4
  1300 mL of solution have ----> X = 2.73 moles of H_2SO_4
  Therefore final solution is 2.73 M".

- One of the Ss correctly solved Items 3B and 3D, but responded incorrectly to Item 3C due to the following reasoning: "... the original solution had 2.1 moles, whereas the final solution has 1.37 moles". This reasoning ignores the fact that the original solution had 1.785 moles dissolved in 850 mL, whereas the final solution has the same number of moles dissolved in 1300 mL.

- Some Ss correctly considered that the addition of 450 mL of water to the 850 mL of the original solution would give them 1300 mL of the final solution. Nevertheless, these Ss considered the density of the final solution to be the same as that of the original solution, that is, 1.38 g/mL.

- One of the Ss gave the following justification for Item 3C: "... what varies is the amount of solvent, so that the <u>solute dissolves more</u> --- the number of moles, however, remain the same ..." (emphasis added).

It was also observed that out of the 9 Ss who responded correctly to conceptual Item 3C, 6 solved Item 3A, 4 solved Item 3B, and 5 solved Item 3D. Results obtained in this experiment provide support for the hypothesis that conceptual understanding manifested through Item 3C is helpful towards the resolution of algorithmic items (3A, 3B, and 3D). Nevertheless, alternative interpretations cannot be ruled out.

<u>Progressive transitions (models) leading to greater conceptual understanding of dilution of solutions</u>

Model 1: Strategies used to calculate molarity in Item 3A, given the mass of the salt dissolved and the density of the resulting solution (N = 20).

Model 2: Strategies used to calculate molarity and molality in Item 3A (N = 15).

Model 3: Strategies used to calculate the molality of the original acid (Item 3D), given the molarity and the density of the acid, in the context of dilution of the solution (N = 8).

Model 4: Strategies used to calculate the molarity of the final solution (Item 3B) after dilution, given the volume and molarity of the original solution, and the amount water added (N = 9).

Model 5: Strategies used to conceptualize that the moles of the acid after the addition of water are the same as before the addition of water (N = 9).

Experiment 4

Table 3 shows the considerable difference between Ss performance on the algorithmic Items (4A and 4C) and the conceptual Item 4B. It was observed that of the 3 Ss who correctly responded to conceptual Item 4B, all 3 solved algorithmic Items 4A and 4C.

Insert Table 3 about here

Progressive transitions (models) leading to greater conceptual understanding of the photoelectric effect

Model 1: Strategies used to calculate the wave number of an electron transition (Item 4A), given the relevant constants and the formula in terms of the wave number (N = 22).

Model 2: Strategies used to calculate the wave length of an electron transition, Item 4A (N = 20).

Model 3: Strategies used to predict if there would be emission of electrons (Item 4C), given the threshold wave length of the metal and the wave length of the impinging light (N = 24).

Model 4: Strategies used to conceptualize that the surface of a metal does not emit electrons, until the frequency of the impinging light is greater than the threshold value, based on a correct response to part (a) of Item 4B (N = 21).

Model 5: Strategies used to conceptualize beyond Model 4, that is, above the threshold frequency, the velocity of the emitted electrons increases as the frequency of impinging light increases, based on a correct response to part (b) or part (c) of Item 4B (N = 13).

Model 6: Strategies used to conceptualize beyond Models 4 and 5, that is, above the threshold frequencey, increasing the light intensity increases the number of electrons emitted per unit time, based on a correct response to part (d) of Item 4B (N = 3). Ss with this Model responded correctly to all 4 parts of Item 4B.

CONCLUSIONS AND EDUCATIONAL IMPLICATIONS

Results obtained in this study show the considerable difference in Ss performance on chemistry problems (mol, gases, solutions, and photoelectric effect) that require algorithmic or conceptual understanding. It was observed that students memorize the scientific laws and the corresponding mathematical equations and then look for values to plug in. Interestingly, student performance decreases even on algorithmic problems in the absence of a readily available algorithmic 'prop' (equation, formula, etc.). This study provides further support to the previous findings that the ability to solve algorithmic problems is not very helpful in developing the ability to solve conceptual problems. On the other hand, the ability to solve conceptual problems does facilitate algorithmic problem solving. Most science educators would agree that algorithmic problems provide certain basic skills and as such should be retained in the curriculum. Nevertheless, the degree to which algorithmic skills should be emphasized and the fraction of class time required to do so, pose a major dilemma for science educators. Item 2A and 2B, in Experiment 2, are particularly illustrative of this dilemma. It is quite clear that the basic algorithmic skill learnt in Item 2A is later useful in conceptual understanding of Item 2B, and the progressive transitions (four models) do manifest some relationship to the manipulative skill learnt in Item 2A. The question remains, when and where to draw the line, with respect to time allocation.

In general, the difference between student performance on algorithmic and conceptual problems can be interpreted as a process of progressive transitions (models) that facilitate different degrees of explanatory / heuristic power to student conceptual understanding, similar to what Lakatos (1970) has referred to as the rational reconstruction of scientific research programs. A parallel is drawn between the methodology of idealization (simplifying assumptions) used by scientists (cf. Niaz, 1991c) and the construction of strategies (models) used by students to facilitate conceptual understanding.

A major educational implication of this study is that the relationship between algorithmic and conceptual problems is not dichotomous but rather characterized by a continuum that consists of sequences of models that facilitate greater conceptual understanding. For example, student understanding of the properties of gases goes through the following closely related models:

1. Algorithmic ability to manipulate three of the variables of Boyle's Law ($P_1V_1 = P_2V_2$) to calculate the fourth variable.
2. In a pV manipulation, the ability to partially conceptualize only the final volume.
3. In a pV manipulation, conceptualize correctly the final volume and pressure, that is, an increase (progressive transition) in conceptual understanding.
4. In a pV manipulation, ability to conceptualize correctly the final volume, final pressure, and the initial pressure ---- further increase in conceptual understanding.

This reconstruction of various strategies (progressive transitions) can provide the teacher a framework to aniticipate as to how student understanding could develop from being entirely algorithmic to conceptual.

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Table 1

Comparison of student ability to solve Items 1A and 1B in Experiment 1 (N = 83)

	Number of students	
Success in solving an Item	Item 1A	Item 1B
Correct	47 (57%)*	18 (22%)
Partially correct	25 (30%)	13 (16%)
Incorrect	11 (13%)	52 (63%)

*Figures in parentheses represent percentages

Table 2

Comparison of student ability to solve Items 3A, 3B, 3C, and 3D in Experiment 3 (N = 60)

Success in solving Item 3A	N	Number of students who solved an Item after having attempted Item 3A		
		Item 3B	Item 3C	Item 3D
Correct (Molarity & molality)	15	8	6	6
Partially correct (Molarity only)	20	-	2	2
Incorrect	25	1	1	-

Table 3

Comparison of student ability to solve Items 4A, 4B, and 4C in Experiment 4 (N = 44)

	Number of students		
Success in solving an Item	Item 4A	Item 4B	Item 4C
Correct	20 (45%)*	3 (7%)	24 (55%)
Partially correct	22 (50%)	23# (52%)	3 (7%)
Incorrect	2 (5%)	18 (41%)	17 (39%)

*Figures in parentheses represent percentages

#Number of students who correctly solved: Part a = 21, Part b = 13, Part c = 4, and Part d = 3