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ABSTRACT

The purpose of this investigation was to identify and describe the differences in the methods used by experts (university chemistry professors) and nonscience major introductory chemistry students, enrolled in a course at the university level, to solve paired algorithmic and conceptual problems. Of the 180 students involved, the problem-solving schema of 20 novices were evaluated using a graphical method to dissect their think-aloud interviews into episodes indicative of solutions to paired problems on density, stoichiometry, bonding, and gas laws. These interviewed novices were classified into four different problem-solving categories (high algorithmic/high conceptual, high algorithmic/low conceptual, low algorithmic/high conceptual, and low algorithmic/low conceptual). Results of these comparisons indicated that there is an indirect relationship between a subject's ability to solve problems, and the time and number of transitions required. As the subjects' ability to solve both algorithmic and conceptual problems improved, less time and fewer transitions between episodes of the problem-solving schema were required to complete the problems. Algorithmic-mode problems always required more time and a greater number of transitions for completion than did conceptual-mode problems, but algorithmic-mode problems were more frequently solved correctly. (Author)

# Differences between Algorithmic and Conceptual Problem Solving by Nonscience Majors in Introductory Chemistry

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# Differences between Algorithmic and Conceptual Problem Solving by Nonscience Majors in Introductory Chemistry

## Abstract

The purpose of this investigation was to identify and describe the differences in the methods used by experts (university chemistry professors) and nonscience major introductory chemistry students, enrolled in a course at the university level, to solve paired algorithmic and conceptual problems. Of the 180 students involved, the problem-solving schema of 20 novices were evaluated using a graphical method to dissect their think-aloud interviews into episodes indicative of solutions to paired problems on density, stoichiometry, bonding, and gas laws. These interviewed novices were classified into four different problem-solving categories (high algorithmic/high conceptual, high algorithmic/low conceptual, low algorithmic/high conceptual, and low algorithmic/low conceptual), and composite graphs of their problem-solving schema were compared to those of the experts' category. Results of these comparisons indicated that there is an indirect relationship between a subjects' ability to solve problems, and the time and number of transitions required. As the subjects' ability to solve both algorithmic and conceptual problems improved, less time and fewer transitions between episodes of the problem-solving schema were required to complete the problems. Algorithmic-mode problems always required more time and a greater number of transitions for completion than did conceptual-mode problems, but algorithmic-mode problems were more frequently solved correctly.

Many difficulties for beginning chemistry students involve problem solving. In most introductory courses, a large amount of information has to be processed and understood by a student to succeed academically. This information can be presented to students in two distinct modes: algorithmic or conceptual. Consequently, a comprehensive understanding of introductory chemistry requires students to excel at problem solving reflective of both types of instruction. What method and how subjects approach this task are fundamental to their success. The question is, do problem-solving schema used by novice students differ as their ability to solve problems in introductory chemistry improve? In order to fully investigate the detailed aspects of this central question, it is necessary to dissect the novices' approach to problem solving. Because this task is so complex, it is necessary to approach the solution in a very logical and categorical manner.

## Problem Solving

Problem solving is a complex process. Learning is a continuous process which is built upon prior knowledge and results in an increased understanding of the subject in question. Instruction in chemistry usually stresses the importance of linking prior knowledge with new information entering the system. The ability to solve problems is also associated with adaptive behavior. Novice problem solvers usually have difficulty in solving problems due to a lack of prior knowledge in a specific content area, not because they simply lack the ability to solve problems (Shuell, 1990a). Shuell (1990b, p. 532) reported that "learning is an active, constructive, cumulative, and goal-oriented process that involves problem solving." The more teachers understand about how students learn, the more effective they will be in achieving high rates of successful performance in problem solving.

Many studies have reflected on how individuals solve selected problems in introductory chemistry, but none has addressed where the difficulties in the problem-solving schema arise as individuals solve problems. Also missing from the published research on problem solving in chemistry, are the similarities and differences in the episodes of the problem-solving strategies used by experts and those used by novices. Neither is it known whether problem-solving practice over a short span of time will result in the development of novice problem-solving schema that more closely resemble those of the expert. Shuell (1990b) reported that even when students are not actively engaged in seeking a solution to a problem, they are still using this time for the purpose of reflection in order to find the appropriate solution. Sweller (1989) concluded that worked examples are more effective when they are repeated over a span of time, than when they are presented only once in an educational setting (i.e., a cyclic mode of teaching mathematics improved student performance). The literature contains evidence that novice problem solvers in chemistry usually have greater success with solving problems of an algorithmic mode than problems having a more conceptual base (Bunce, 1993; Nakhleh, 1993). Niaz and Robinson (1992) concluded that student training in algorithmic-mode problems did not guarantee successful understanding of conceptual problems. According to this study (Niaz & Robinson 1992, p. 54), "algorithmic and conceptual problems may require different cognitive abilities".

## Purpose

This investigation sought to establish the similarities and differences in the ways novices solved algorithmic and conceptual problems in introductory chemistry. The expected outcome of this investigative procedure was to establish a comparison based on different categories of novices and their respective approaches to solving paired algorithmic and conceptual problems.

## Rationale

Novice problem solvers in chemistry usually have greater success with solving problems of an algorithmic mode than problems having a more conceptual base (Bunce, 1993; Nakhleh, 1993). At present, it is unknown whether problem-solving practice over a short span of time will develop novices' problem-solving schema to more closely resemble that of experts'. What is known is that there are different categories of novice problem solvers in chemistry. What needs to be documented is how the schema differ among categories of problem solvers.

The topics for the problems developed for this study were those typically found in introductory college chemistry: density, stoichiometry, bonding, and gas laws. These four topics were chosen because of their frequency of occurrence in research literature and in introductory chemistry courses. Also, for the purposes of replication and internal validity, six of the eight problems have been used in previous research projects (Nakhleh, 1993; Nakhleh & Mitchell, 1993; Nurrenbern & Pickering, 1987; Sawrey, 1990).

## Significance of the Study

The main focus of this study was to examine in detail the novice's strategy for solving chemistry problems using a think-aloud protocol. Many investigators have tried to teach students different ways to be successful in solving problems in introductory chemistry, but none have attempted to evaluate *exactly* what a student does with the information learned. This study compared categories of novice problem solvers at the episodic level within a schema. The categories of students used in this study were similar to those used in previous research

(Nakhleh, 1993): high algorithmic/high conceptual (HA/HC), high algorithmic/low conceptual (HA/LC), low algorithmic/high conceptual (LA/HC), and low algorithmic/low conceptual (LA/LC). Also, the analysis was presented more quantitatively than is usually reported for this type of think-aloud assessment.

## Research Questions

This study sought to answer the following research questions:

1. What general strategies do experts and the following categories of novice problem solvers use to obtain solutions to paired algorithmic and conceptual problems in introductory chemistry: high-ability algorithmic/high-ability conceptual; low-ability algorithmic/high-ability conceptual; high-ability algorithmic/low-ability conceptual; and low-ability algorithmic/low-ability conceptual? (What are the similarities and differences in these strategies?)
2. How do the general problem-solving procedures used by high-ability algorithmic/high-ability conceptual, low-ability algorithmic/high-ability conceptual, high-ability algorithmic/low-ability conceptual, and low-ability algorithmic/low-ability conceptual novices compare to the general problem-solving procedures used by the expert in solving paired algorithmic and conceptual problems?

## Research Design and Instrumentation

The students (n = 179) who participated in this study were enrolled in a first semester introductory chemistry course designed for the nonscience major at The University of Texas at Austin, a large southwest research institution. There were no special admission policies related to this course; however, successful completion of the course may not satisfy a degree requirement for a student seeking a science or engineering degree. All students were required to attend three hours of lecture per week, and no laboratory session was associated with this course.

Twenty students, ten males and ten females of the lecture class (experimental group), were selected for an independent assessment of their approach to solving selected algorithmic and conceptual problems chosen from topics appropriate for a course in introductory chemistry. Criteria used for selection of this subgroup were based on information obtained from the initial student profile. Attempts were made to assure that the selected subgroup was representative of the experimental group as to gender and college enrollment. According to Arney (1990), stratification by college enrollment is a useful technique for making comparisons between subgroups of a population. A stratified random sample of students was therefore selected based on the percentages reported in Table 1. In this study the large-group lecture class was stratified and proportionally sampled according to the five colleges with the largest representation: Business (three males, three females); Communications (one male, one female); Engineering (two males, one female); Liberal Arts (three males, three females); and Natural Sciences (one male, two females). (Students from the Colleges of Education and Fine Arts and from some other smaller divisions were omitted, because the number of students represented by all these groups combined was less than 9% of the initial sample.) Also, two professors (both involved in teaching freshman-level courses offered by the Department of Chemistry and Biochemistry) were chosen to participate as expert problem solvers in this investigation.

Table 1
*Distribution of Students by College Enrollment*

| | Experimental Group | | | Interview Sample | | |
|---|---|---|---|---|---|---|
| | Percentage | Number | | Percentage | Number | |
| College | | Female | Male | | Female | Male |
| Liberal Arts | 31.1 | 31 | 25 | 30.0 | 3 | 3 |
| Business | 28.9 | 24 | 28 | 30.0 | 3 | 3 |
| Engineering | 11.1 | 6 | 14 | 15.0 | 1 | 2 |
| Communication | 10.6 | 7 | 12 | 10.0 | 1 | 1 |
| Natural Sciences | 9.4 | 10 | 7 | 15.0 | 2 | 1 |
| Education | 3.3 | 4 | 2 | 0.0 | 0 | 0 |
| Fine Arts | 2.8 | 2 | 3 | 0.0 | 0 | 0 |
| Other | 2.8 | 4 | 1 | 0.0 | 0 | 0 |
| Totals | 100.0 | 88 | 92 | 100.0 | 10 | 10 |

Selected novices and experts solved four sets of paired algorithmic and conceptual problems (see below) on specific topics at the time of the interviews: density, stoichiometry, bonding, and gas laws. In order to assure that all interviewed students qualified as novices, lecture attendance and problem-solving ability were documented by the collection of 13 in-class assignments completed by the students on selected topics, which were reflective of didactic information presented in the lecture session. (These in-class assignments also consisted of paired algorithmic and conceptual problems, in order to allow the novices to experience this type of presentation of information prior to the interviewing process.)

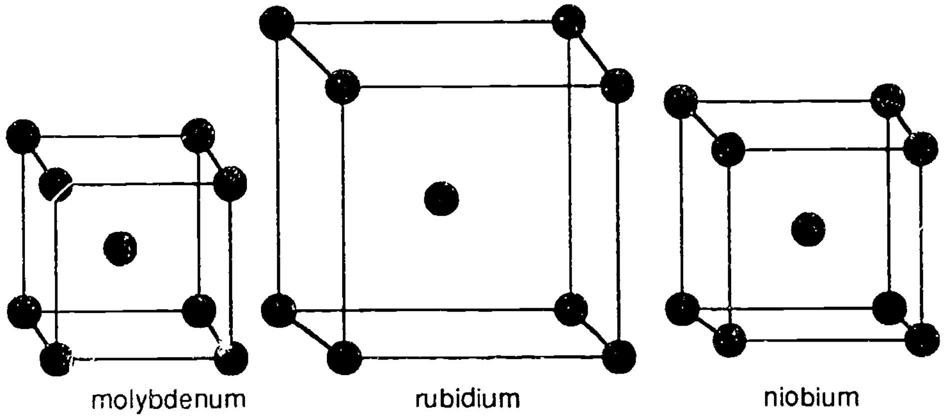
## Density

1. Potassium, vanadium, and iron crystallize in a body centered cubic unit cell. Given the lengths of the unit cell edges and the atomic weight listed below, which of these elements has the <u>highest</u> density (is the most dense)?

potassium: a = 5.250 Å
AW = 39.098
vanadium: a = 3.024 Å
AW = 50.942
iron: a = 2.861 Å
AW = 55.847

(A) potassium
(B) vanadium
(C) iron*
(D) They all have the same density.
(E) Not enough information is given.

2. The drawings below are drawn to scale and illustrate the crystal structure of rubidium, niobium, and molybdenum. The atomic weights of these elements are roughly equivalent. Which of the elements has the <u>lowest</u> density (is the least dense)?



(A) niobium
(B) rubidium*
(C) molybdenum
(D) They all have the same density.
(E) Not enough information is given.

## Stoichiometry

1. Calculate the maximum weight of $NH_3$ that could be produced from 1.9 mol of hydrogen and excess nitrogen according to the following reaction:

$N_2 + 3H_2 \dashrightarrow 2\ NH_3$

(A) 15 g
(B) 28 g
(C) 22 g*
(D) 30 g
(E) 17 g

2. Any quantity of Cu in excess of one mole will always react with two moles of $AgNO_3$ to produce one mole of $Cu(NO_3)_2$ and two moles of Ag. Therefore we know that 1.5 moles of Cu will react with two moles of $AgNO_3$ to produce 215.74 grams of Ag. Which of the following concepts is the only concept NOT associated with these statements?

(A) Chemical reactions involve the rearrangement of atoms about one another.
(B) In an ordinary chemical reaction mass is not created or destroyed.
(C) Identical compounds are always composed of the same elements in the same proportion by mass.
(D) Moles of chemical compounds are always conserved in balanced equations.*
(E) The number of moles of products formed in this case are determined by the number of grams of $AgNO_3$ available.

## Bonding

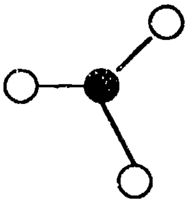
1. Given the following information regarding an unknown molecule, identify which compound would be the most likely to form.

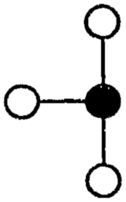
Total valence electrons = 26
Bonded pairs of electrons = 3
Hybridization = $sp^3$
Predicted geometrical shape = tetrahedral

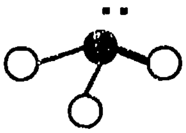
(A) $NH_4^+$
(B) $NF_3$ *
(C) $PF_5$
(D) $CCl_4$
(E) $ClO_3^-$

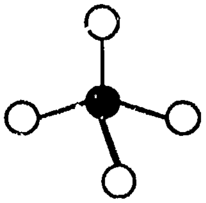
2. Which of the diagrams below correctly depict the geometrical shape and bond angles of ammonia, $NH_3$? Explain.

● = N ○ = H


(A)


(B)


(C)*

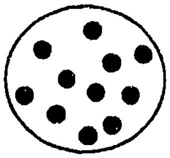

(D)

Gas Laws

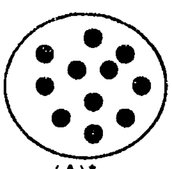
1. 0.100 mole of hydrogen gas occupies 600. mL at 25 °C and 4.08 atm. If the volume is held constant, what will be the pressure of the sample of gas at -5 °C?

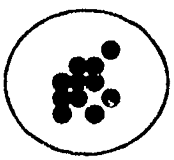
(A) 4.54 atm
(B) 3.67 atm*
(C) 6.00 atm
(D) 2.98 atm
(E) 4.08 atm

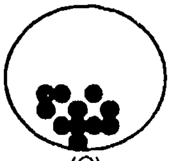
2. The following diagram represents a cross-sectional area of a rigid sealed steel tank filled with hydrogen gas at 20 °C and 3 atm pressure. The dots represent the distribution of all the hydrogen molecules in the tank.

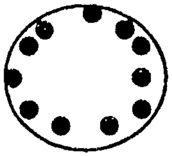


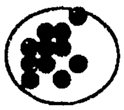
Which of the following diagrams illustrate one probable distribution of molecules of hydrogen gas in the sealed steel tank if the temperature is lowered to -5 °C? The boiling point of hydrogen is -242.8 °C.


(A)*


(B)


(C)


(D)


(E)

Both novices (n = 20) and experts (n = 2) solved the paired algorithmic and conceptual problems using a think-aloud protocol. (Novice subjects (n = 20) were selected using a stratified random sampling technique (based on college enrollment) of the large-group lecture class.) As the interviewed subjects solved each problem, their problem-solving schema were graphed using an incident identification tool. The tool used in this study was a modification of one developed by a mathematics educator, Alan Schoenfeld (Woods, 1992). This method was used to evaluate three variables: the time needed to complete a solution to a problem, the number of transitions within a scheme, and the rate of these transitions over time. The graphs were designed in the following manner: abscissa--time (0-10 minutes) and ordinate--problem-solving episodes (read, define, set up, solve, check). Graphs were completed for all subjects at the time of the original interviews. The interviews were taped and subsequently transcribed for purpose of verification of accuracy. From similarities and differences regarding these aspects of the interviewed subjects' problem-solving schema, decisions were made as to how students solved these problems and where difficulties arose. This evaluation laid the foundation for a more quantitative interpretation of differences between different types of problem solvers than is usually reported in the literature regarding problem solving.

In addition to the graphic analyses, the students were evaluated on the basis of their Scholastic Aptitude Test (SAT) scores, cognitive developmental level, and specific background variables (e.g., college enrollment and gender). These variables, along with the information gained from the graphic analyses, were used to identify specific aspects of problem solving that presented obstacles to the novice. Identification of these difficulties may serve to provide useful information to instructors of introductory chemistry, so that they may be better prepared to educate the beginning chemistry student at the university level.

## Results and Discussion

Data were collected for the entire large-group (n = 179) lecture class on 13 in-class exercises, which consisted of paired algorithmic and conceptual problems, to insure that the selected interview sample (n = 20) was reflective of the whole. Mean scores on these exercises were calculated for all students in each college. In all cases the algorithmic score was higher than the conceptual score (see figure 1). Correctness of student responses on the four-paired interview questions led to the classification of the different types of problem solvers in the interview sample. An interviewed subject who solved three or four of the algorithmic or conceptual problems correctly was classified as "high"; and correspondingly, a subject who solved only one or two problems correctly was classified as "low". Table 2 depicts the distribution of novices according to their problem-solving ability.

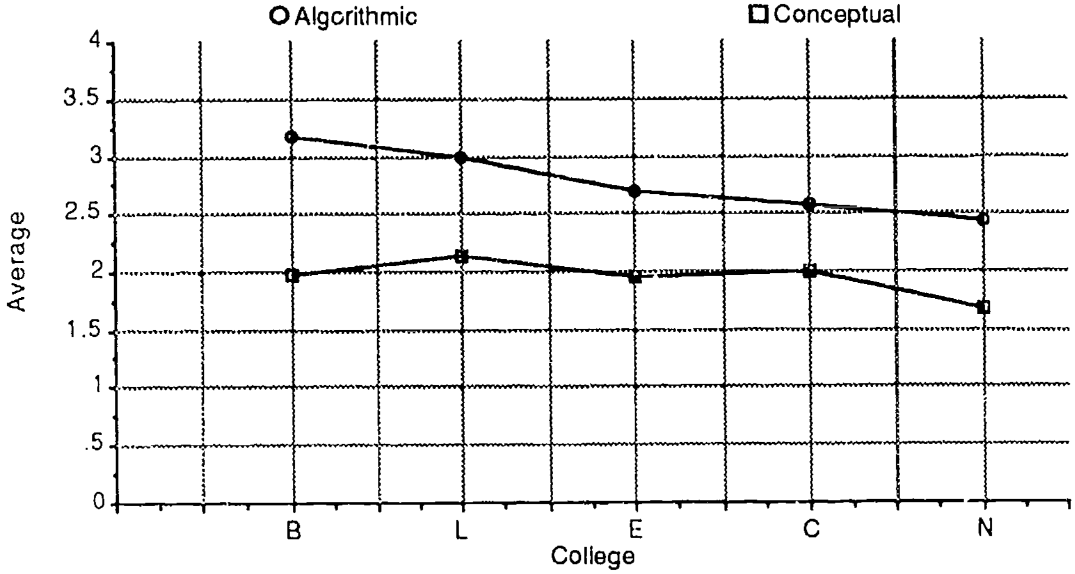


*Figure 1.* Algorithmic and conceptual means for sample colleges. (B = Business, L = Liberal Arts, E = Engineering, C = Communications, N = Natural Sciences)

Table 2
*Categorization of Novice's Algorithmic vs. Conceptual Problem-Solving Ability*

| | | Algorithmic Ability | | |
|---|---|---|---|---|
| | | High | Low | Totals |
| Conceptual Ability | High | 10% | 0% | 10% |
| | Low | 65% | 25% | 90% |
| Totals | | 75% | 25% | 100% |

*Expert Subject*

Figures 2 and 3 represent examples of incident identification graphs depicting the problem-solving schema of an expert, a university freshman-level chemistry professor. Figure 2 characterizes how an algorithmic mode problem was solved, and Figure 3 characterizes how a conceptual problem was solved by a typical expert. The time needed to complete an algorithmic problem for the expert subject was 1 minute and 30 seconds (i.e., 1:30), and the time needed to complete a conceptual problem was 0 minutes and 49 seconds (i.e., 0:49). The mean number of transitions (i.e., movement from one episode to another) for the algorithmic and conceptual problems were three and two, respectively. The mean rates (i.e., the number of transitions per minute required to solve a problem) for the algorithmic and conceptual problems were 2.1 and 2.0, respectively. The total time, number of transitions, and rate of transitions were greater for the typical algorithmic-mode problem than the conceptual-mode problem solved by the expert, as can be seen by comparing Figure 2 with Figure 3.

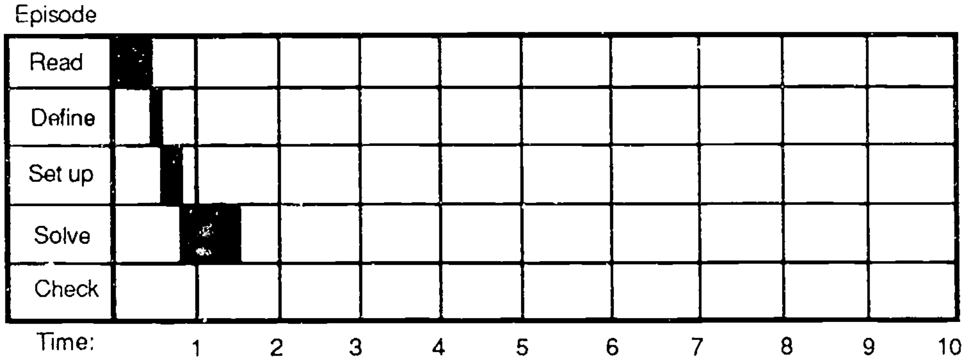


*Figure 2.* Algorithmic episodic graph of a typical expert.

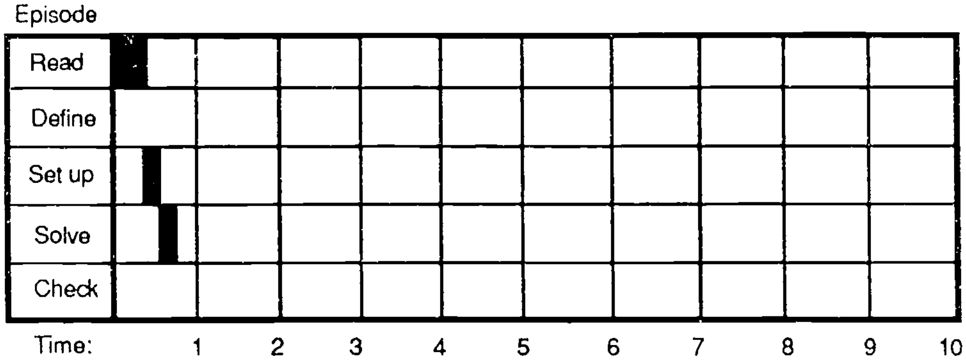


*Figure 3.* Conceptual episodic graph of a typical expert.

*High Algorithmic/High Conceptual Subject*

Figures 4 and 5 represent examples of incident identification graphs depicting the problem-solving schema of a typical HA/HC student. To become a member of this category, the interviewed subject had to correctly solve three or four of the algorithmic and three or four conceptual-mode problems. Figure 4 characterizes how an algorithmic-mode problem was solved, and Figure 5 characterizes how a conceptual problem was solved by a typical HA/HC novice. The time needed to complete an algorithmic problem for the HA/HC subject was 2:42, and the time needed to complete a conceptual problem was 2:18. The mean number of transitions for the composite algorithmic and conceptual problems were five and four, respectively. The mean rates for the composite algorithmic and conceptual problems were 2.0 and 1.7, respectively. The total time, number of transitions, and rate of transitions were greater for the typical algorithmic-mode problem, than for the typical conceptual-mode problem solved by students classified as HA/HC problem solvers. (This trend was similar to that calculated and graphically displayed from the incident identification graphs of the experts.)

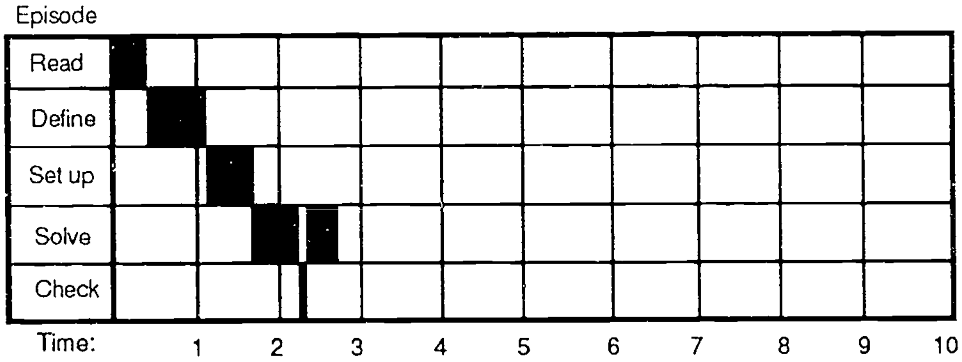


*Figure 4.* Algorithmic episodic graph of a typical HA/HC novice.

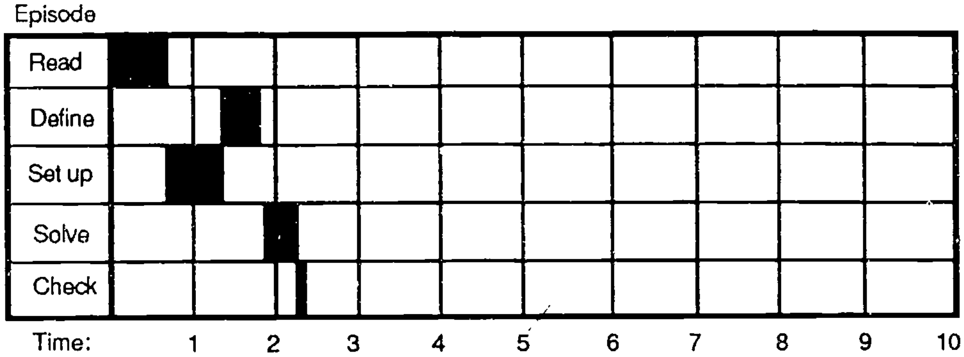


*Figure 5.* Conceptual episodic graph of a typical HA/HC novice.

*Low Algorithmic/High Conceptual Subject*

The sample (n = 20) selected from the experimental class (n = 180) for this study failed to produce any subjects who qualified as a member of this classification, LA/HC. To have qualified as a member of this classification, subjects would have needed to have solved correctly two or less algorithmic-mode problems and three or four conceptual-mode problems. Consequently, no graphs could be drawn for this group of novices. This result is not surprising since only 4.5% of the experimental class (i.e., eight students) met the requirements necessary for membership in this category.

*High Algorithmic/Low Conceptual Subject*

Figures 6 and 7 represent examples of incident identification graphs depicting the problem-solving schema of a HA/LC student. To become a member of this group, the subject must solve three or four algorithmic-mode problems correctly, and only two or less conceptual-mode problems must be correctly solved. Figure 6 characterizes how an algorithmic mode problem was solved, and Figure 7 characterizes how a conceptual problem was solved by a typical HA/LC novice. The time needed to complete an algorithmic problem for the HA/LC subject was 4:34, and the time needed to complete a conceptual problem was 2:19. The mean numbers of transitions for the algorithmic and conceptual problems were eight and four, respectively. The mean rates for the algorithmic and conceptual problems were 1.8 and 1.9, respectively. The total time and number of transitions were greater for the typical algorithmic-mode problem, than for the typical conceptual-mode problem; however, the rate of transition for the conceptual-mode problem was greater than for the algorithmic-mode problem for the HA/LC novice.

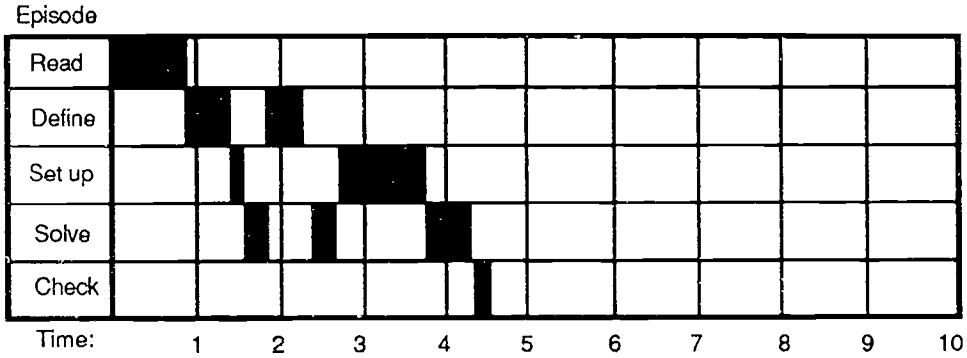


*Figure 6.* Algorithmic episodic graph of a typical HA/LC novice.

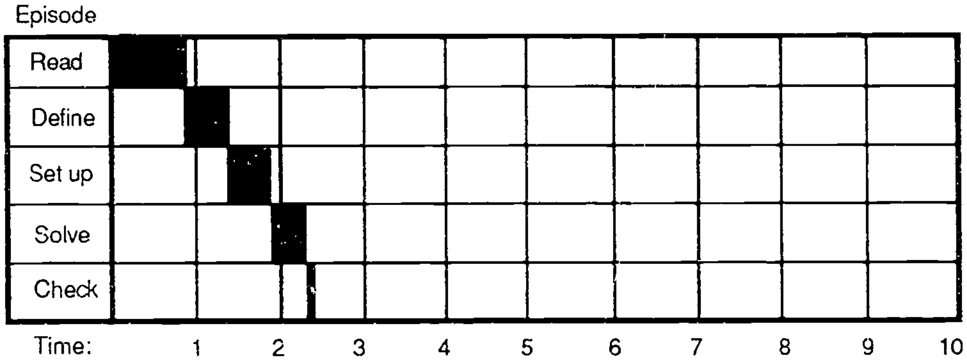


*Figure 7.* Conceptual episodic graph of a typical HA/LC novice.

*Low Algorithmic/Low Conceptual Subject*

Figures 8 and 9 represent examples of incident identification graphs depicting the problem-solving schema of a typical LA/LC novice. Students who failed to correctly solve more than two algorithmic and conceptual-mode problems fell into this category. Figure 8 characterizes how an algorithmic mode problem was solved, and Figure 9 characterizes how a conceptual problem was solved by a typical LA/LC novice. The time needed to complete an algorithmic problem for the LA/LC subject was 5:48, and the time needed to complete a conceptual problem was 3:15. The mean numbers of transitions for the algorithmic and conceptual problems were twelve and seven, respectively. The mean rates for the algorithmic and conceptual problems were 2.1 and 2.2, respectively. The total time and number of transitions were higher for the typical algorithmic than the conceptual problem; however, the rate of transition was lower for the algorithmic problem than the conceptual problem for the LA/LC student. This trend was similar to that seen for the other group of LC novices (i.e., HA/LC group).

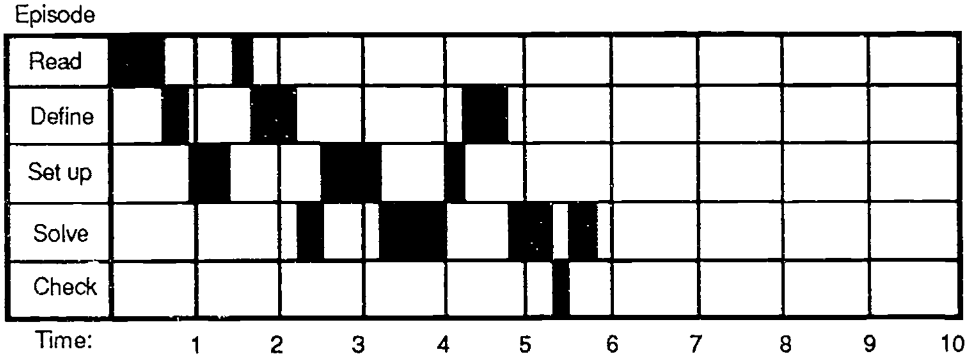


*Figure 8.* Algorithmic episodic graph of a typical LA/LC novice.

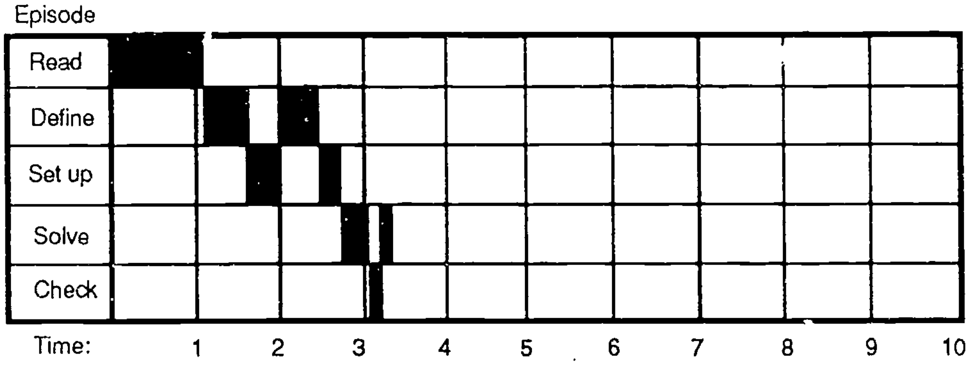


*Figure 9.* Conceptual episodic graph of a typical LA/LC novice.

Comparing the composite incident identifications graphs from all problem-solving groups of subjects, it is evident how quickly and how effortlessly (i.e., with few transitions between episodes) the expert is able to solve algorithmic and conceptual problems relative to topics in introductory chemistry for the nonscience major. By contrast, it is also evident how much time and effort is expended by the lower-performance groups. Not only do the times and number of transitions increase as the problem-solving performance level decrease, but the rate of transitions, when algorithmic and conceptual problem-solving modes are compared, appear to be similar along the lines of HCs (e.g., expert and HA/HC groups) and LCs (e.g., HA/LC and LA/LC groups).

Figures 10, 11, and 12 graphically depict data as a function of the interviewed subjects' membership into the problem-solving categories studied. Figure 10 presents comparisons of the mean total time; Figure 11, the mean number of transitions; and Figure 12, the mean rates for the average of all four algorithmic and conceptual problem pairs. In all cases the mean total time (see Figure 10) for the typical algorithmic-mode problem was always longer than for the corresponding conceptual-mode problem, regardless of the classification of the subject. Likewise, the mean number of transitions (see Figure 11) for an algorithmic problem always exceeded that needed to solve the corresponding conceptual problem, regardless of the problem-solving performance level of the subject.

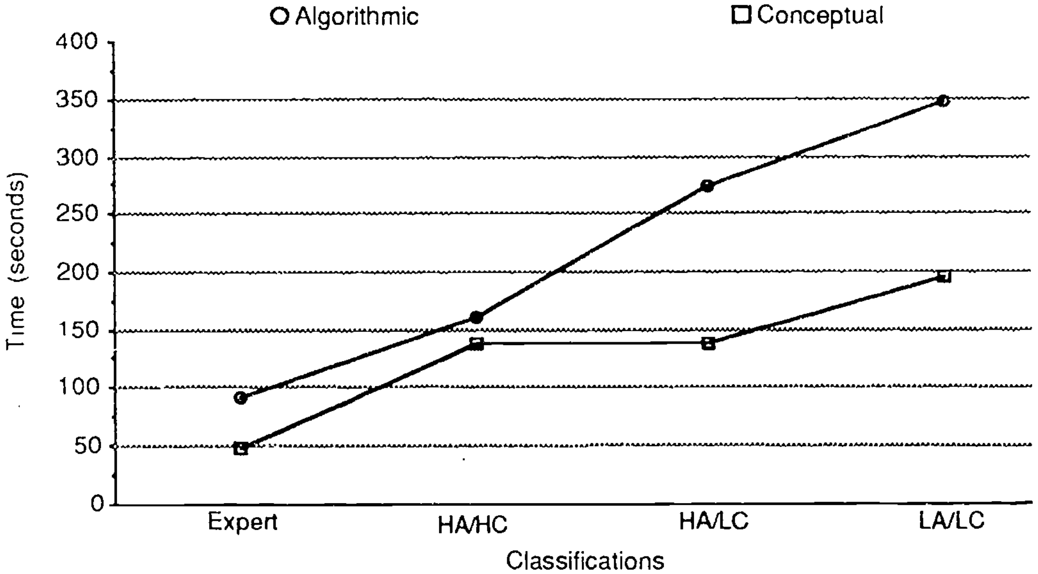


*Figure 10.* Mean total time needed for different categories of subjects to solve paired algorithmic and conceptual problems.

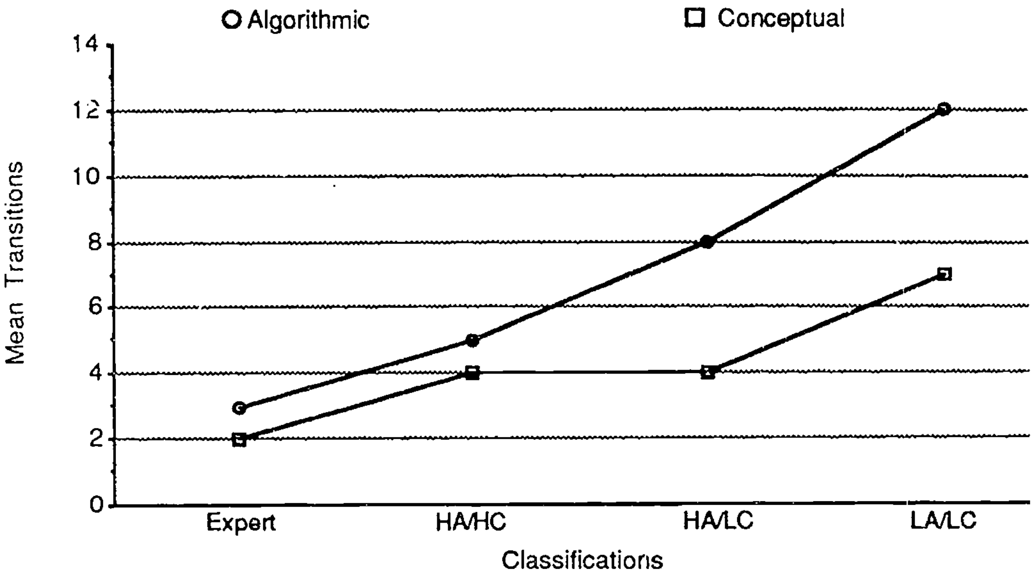


*Figure 11.* Mean number of transitions used by different categories of subjects in solving paired algorithmic and conceptual problems.

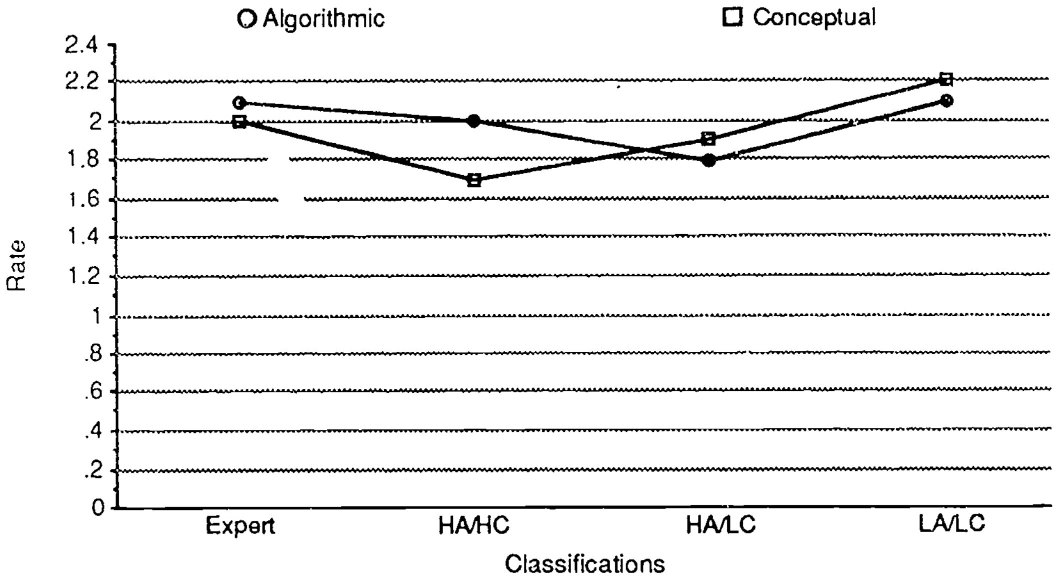


*Figure 12.* Mean rate calculated for different categories of subjects to solve paired algorithmic and conceptual problems.

When these results were compared to the results for the calculated rate (see Figure 12), all problem-solving performance levels are leveled to an apparent constant (near zero slope), or a level of approximately 2 transitions per minute of time required to solve the problem. In other words, even though problem-solving time increased as the problem was solved, so did the number of transitions made while the problem was being solved. Also, as displayed in Figures 6-9, the mean rates (see Figure 12)of the HA/LC and LA/LC novices for the conceptual-mode problems were higher than that for the corresponding algorithmic-mode problem. This is the opposite trend than that seen in Figure 12 for the expert and HA/HC categories. In the latter cases the mean rate of transitions for the algorithmic-mode problem exceeded that for the corresponding conceptual-mode problem (see Figures 2-5).

Figures 13 and 14 compare the problem-solving schema for each of the four available groups of problem solvers (i.e., expert, HA/HC, HA/LC, and LA/LC). Figure 13 compares the typical algorithmic problem-solving episodes used by members of each group, and Figure 14 compares the typical conceptual problem-solving episodes of each group. The similarity of the curves on the graph for the expert and HA/HC groups can be seen in Figure 13, as can the similarity of the curves on the graph for the HA/LC and LA/LC groups. In Figure 14, there appears to be a discrepancy on the graph at the point of "set up" for the HA/HC subgroup, but this may not be representative of the HA/HC members in general. This anomaly may be accounted for by the fact that one of the two novices belonging to this subgroup was momentarily confused while "setting up" the conceptual-mode density problem. Consequently, any anomaly associated with this group (HA/HC) has been magnified disproportionately. (This same anomaly can be seen in Figure 16.)

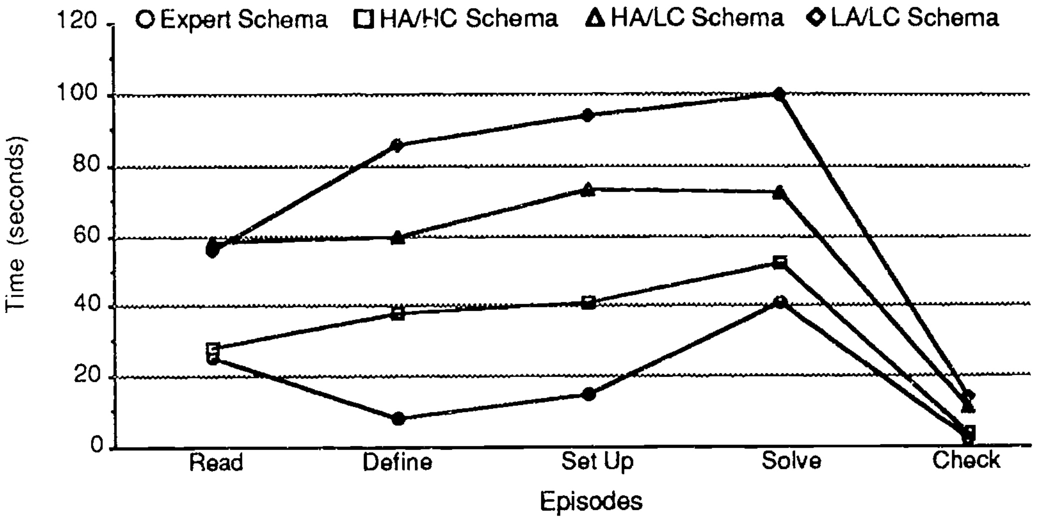


*Figure 13.* Time required within each episode of an algorithmic problem for each subgroup.

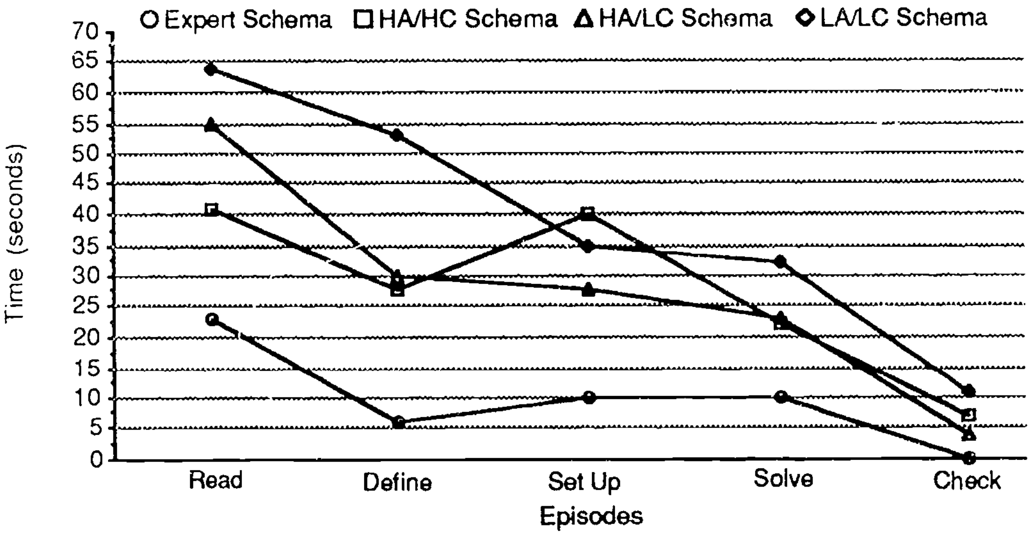


*Figure 14.* Time required within each episode of a conceptual problem for each subgroup.

Figures 15 and 16 are different representations of Figures 13 and 14. These two figures display the data in a way that allowed for a comparison of the expert group with the novice groups. A progressive divergence of the curves are seen in Figures 15 and 16. In the cases of the typical expert, the problem-solving episodes for both the algorithmic and conceptual problems were closely related in time required to solve the problems, and each episode only consisted of a minimal amount of time. In the cases of the typical LA/LC novice, the total time required to solve the problems and the time within each episode increased. As the novice groups progressed from HA/HC to LA/LC, the amount of time required within each episode increased (in general).

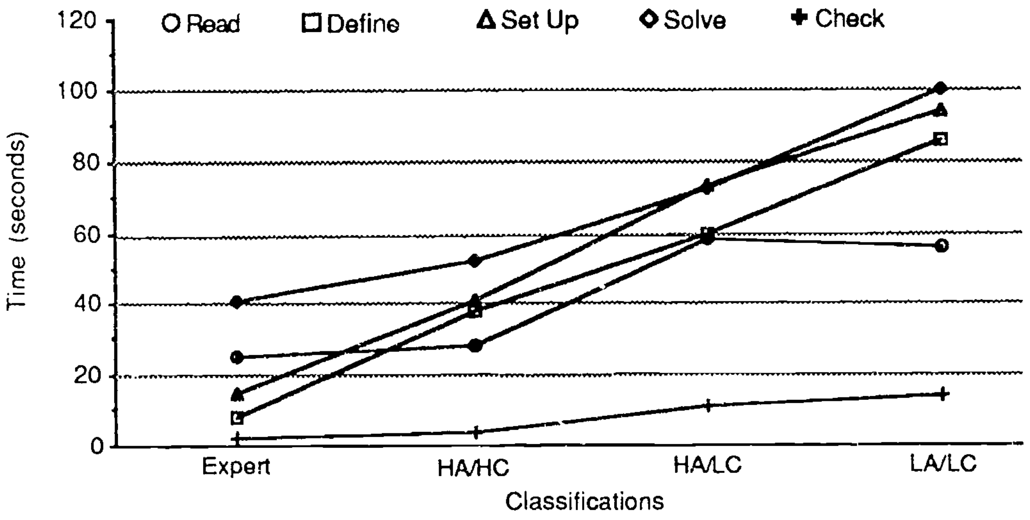


*Figure 15.* Time required for each subgroup to solve a typical algorithmic problem.

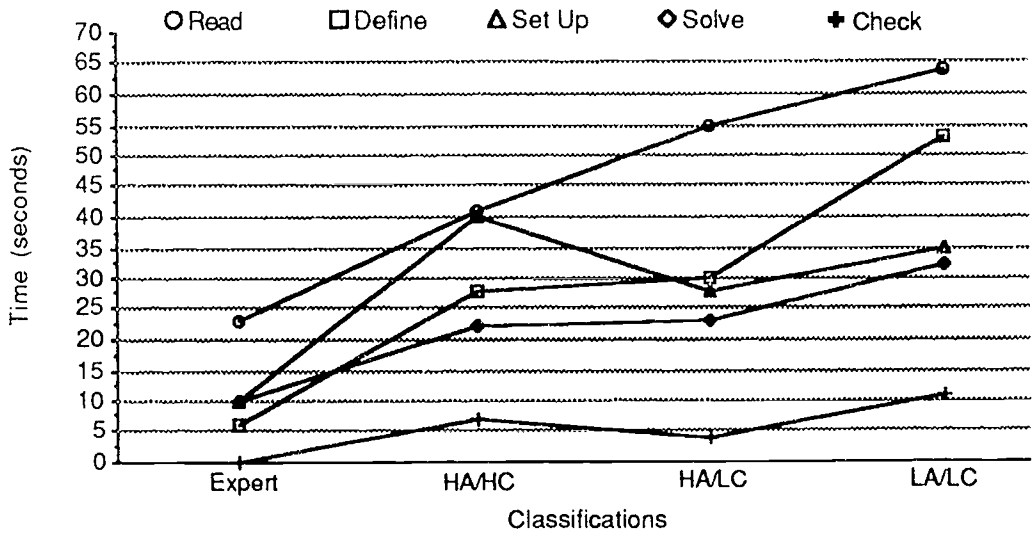


*Figure 16.* Time required for each subgroup to solve a typical conceptual problem.

There were obvious differences in the ways members of all classifications of problem solvers completed problems typically found in introductory chemistry courses. Even though there were distinct differences in the ways the different groups solved problems, there were also similarities between the subjects in expert and HA/HC categories and between the subjects in the HA/LC and LA/LC categories of problem-solvers, especially when algorithmic-mode problems were solved (see Figure 13). Figure 13 depicts the similar "reading" and "checking" times required by the two HA/HC groups (i.e., the experts and the HA/HC novices), and the similar "reading" and "checking" times required by the two LC groups (i.e., the HA/LC and LA/LC novices). In most instances, as problem-solving ability improved, the times required and number of transitions needed to complete a problem decreased.

## Conclusions

Not only did subjects solve algorithmic and conceptual problems differently, but also there was a difference in the way different categories of problem solvers found solutions to problems. Progressing from the experts through the various categories of novice problem solvers (i.e., HA/HC, HA/LC, and LA/LC), not only did the times needed to solve problems increase, but so did the number of transitions needed to solve those problems. This trend was apparent for both the algorithmic and conceptual problem modes (see Figures 10 and 11).

The interpretations of the incident Identification graphs led to the following results: 1) problem-solving time: HA/HC < HA/LC < LA/LC; 2) number of transitions: HA/HC < HA/LC < LA/LC; and 3) rate of transitions (algorithmic): LA > HA; and 4) rate of transitions (conceptual): LC > HC. It is interesting to note that in this study as in similar studies (see Nakhleh, 1993 and Nakhleh & Mitchell, 1993), few (if any) LA/HC students enroll in introductory chemistry courses. According to Nakhleh and Mitchell (1993), these students are "more interested in the concepts than in algorithmic problem solving, "and this population (the typical nonmajor) is a rich source of recruits for various scientific disciplines. However, they do not seem to be enrolling in the courses that are designed especially for them. On the other hand, perhaps this type of problem solver is simply very rare throughout the world of academe. Putting a greater emphasis on the conceptual aspects of the study of chemistry, by separating it from the more algorithmic portion of the course, targeted what Tobias (1990) referred to as the "second-tier students". Results showed that for all stratifications of students, chosen by college enrollment, each (on the average) scored higher on the algorithmic than the conceptual problems. Students who fall into the HA/HC category represent what most instructors would call the "best" students. These students usually succeed regardless of the type of instruction or testing situation.

One drawback to the interpretation of think-aloud interviews is that they are usually very subjective. The graphical method used in this study alleviates this problem. By employing this method, researchers have an opportunity to evaluate how students solve problems on a more systematic and quantitative basis. This graphical method has the major advantage that it can be completed at the time of the interview. Also, the information gained from the use of this method allows for documentation of specific problem-solving differences between categories of problem solvers. No longer do we need to limit comparisons between different classifications of problem solvers to simply correct or incorrect responses. We now have a simple graphical method that can lead us to a detailed specification of the differences in the ways that both algorithmic and conceptual chemistry problems are solved. This method has the added advantages that it permits replication and easily allows for determination of interrater reliability.

The most prominent differences observed in this study were revealed when the interviewed students were classified into problem-solving groups (categories). The groups chosen were those reported by Nakhleh (1993) and Nakhleh and Mitchell (1993), HA/HC, LA/HC, HA/LC, and LA/LC, and the additional classification for the group of experts. None of the interviewed students could be classified as LA/HC, but this was not a surprise since only 4.5% of the entire class qualified as members of this category. The strategies used by novice problem solvers became obvious when their problem-solving schema were graphed using an incident identification tool to depict the different episodes and the time spent within each episode.

Comparing the graphs of different groups of novices with those of the expert problem-solvers reveals that the time needed to solve both the algorithmic and conceptual problems continually increases as the problem-solving performance of category members decreases. Also, this same trend is observed when the number of transitions between episodes is recorded. In all cases, more time and more transitions are required to solved algorithmic-mode problems, than are required for their corresponding conceptual paired problem. This result is explained by the fact that most conceptual-mode problems are dependent upon specific knowledge. Typically, success on a conceptual-mode problem is dependent upon prior knowledge; for example, a known definition or relationship. In contrast, the algorithmic-mode problem sometimes can be solved by use of trial-and-error even if the person is not sure of the algorithm or relationships needed to solve the problem. Comparing the graphs of Figures 2-9, it is obvious that experts tend to arrive at answers in a minimal amount of time and with few transitions. On the other hand, novices require more time and make more transitions to solve problems regardless of the correctness of the outcome.

When the different groups of novices are compared to each other and with the dissected problem-solving schema of the expert, a continuum is apparent. This finding supports the results of other researchers (e.g., Camacho & Good, 1989; Pitt, 1983). In all cases the same episodes are used by all groups of problem solvers. What differentiates members of the different groups is the process that is used. One can observe from the graphs that the LA/LC novices appear to have difficulty following a direct pathway, which is clearly evident in the cases of the HA/HC and expert groups. The typical LA/LC student appears to shift back and forth between episodes, especially when attempting to solve an algorithmic-mode problem. Associated with this less-than-direct approach is the LCs' diminished success on correctly solved problems.

Nakhleh and Mitchell (1993) reported classification of students comparable to the ones identified in this study. In their study, 43.3% of the first-year chemistry students were HA/HC; 5.0% were LA/HC; 41.7% were HA/LC; and 10.0% were LA/LC. In their research, more than 50% of the students were classified into the low conceptual category. In this study, over 75% of the students qualified as low conceptual subjects. This result serves to demonstrate that the majority of the students enrolled in introductory chemistry courses do not understand or fail to apply chemistry concepts correctly. Only 4.5% of the experimental class (0.0% of the interviewed subjects) were classified as belonging to the LA/HC category. Students fitting this classification perhaps are students who Tobias (1990) referred to as "second-tier students". It may be pointless to gear curriculum for such a small population of students. It appears to be the rare (or unusual) student who understands the concepts, but lacks the ability to formulate a mathematical solution to an algorithmic problem. In light of the results of this research, it would behoove instructors to spend more time improving students' conceptual base, than attempting to teach a few students how to overcome their problems in mathematics or to apply prescribed algorithmic strategies. Also in this study, 68.4% of the students in the experimental class qualified as members of the HA category. This result confirmed the published results from studies by Bunce (1993) and Nakhleh (1993), who also found evidence that novice problem solvers usually have greater success with solving algorithmic-mode problems than problems having a more conceptual base in introductory chemistry. Niaz and Robinson (1992) also concluded that training in algorithmic-mode problems does not guarantee the understanding of the conceptual base of chemistry.

Dissecting the general problem-solving procedures of the different classifications of problem solvers illuminates the similarities and differences related to the third research question. In Figure 13, similarities are apparent between the algorithmic schema of the expert and HA/HC groups, and the two low conceptual problem-solving groups. The same general curves on the graph are seen for performance among members of the high-conceptual groups and among members of the low-conceptual groups. The curves on the graph for solving a conceptual-mode problem, regardless of problem-solving group, appear similar with one exception at the "set up" episodic point for the HA/HC novice (see Figure 14). Excluding this point, it appears that persons tend to solve a conceptual-mode problem in the same way with the major difference being time required to solve the problem. In other words, when solving a conceptual-mode problem, after its initial reading, the time required to complete the problems proceeds rapidly. Another similarity between the solving of algorithmic and conceptual problem pairs is that little time is spent checking the results by any of the groups of problem solvers investigated.

## Implications

Lecture is a very efficient way to convey important information to students in the shortest time frame available. This fact does not mean that the large-lecture hall must be a static learning situation. In this study, mixing the delivery of didactic information with appropriate demonstrations (either live or through visual media), along with letting the students participate, not only kept these students in class (only 9 of 180 students withdrew from the course), but also kept their respective averages relatively high (only six grades of "F" were recorded, four of which were received by students who failed to take the second and final examinations). Zoller (1993) reported that students need to experience chemistry by actively participating in classroom activities either through team work situations, class discussion, and/or eclectic examinations. However, all of these methods are quite physically and emotionally demanding on the instructor.

In 1991, the National Science Foundation (NSF) published data that revealed that over the ten year period, between 1980 and 1989, the number of baccalaureate degrees in science and engineering decreased by approximately 3% and computer science degrees increased by almost 12%. The authors projected that the probable careers of the 1990 American Freshman would be in engineering (27%) and business (14%); only 8.4% of the 1990 Freshman were predicted to receive a baccalaureate degree in Natural

Sciences. With this decrease of demand at the university level, and the fact that only 40% of the current high school population are enrolled in high school chemistry, what can be done to encourage more students to enroll in chemistry courses? Rowe (1983) suggested to get chemistry off the "killer list", that first students must master relevant chemistry concepts and that educators could help this process by standardizing the system of symbolic representation (i.e., try to use the same notations that are present in the textbook used by the students). Other suggestions included encouraging the use of labels while working problems, talking "chemistry" with others, the use of more visual information, and pointing out to nonchemistry majors the chemistry content that is embedded into their own majors.

In light of the above results, one needs to question the purpose of an introductory chemistry course for nonscience majors. Is the purpose to provide the knowledgeable nonscience major a way to meet a requirement for a degree, or is it to further the education of the student who has a minimal background in the subject? Some students who enroll in nonscience major courses do so as a means to boost their grade point average, and in doing so, then deny themselves an opportunity to further their education. This is not to say that introductory chemistry courses for nonscience majors should be canceled, but it should be labeled as an "introductory course" and attended by students who do not qualify for the first semester of general chemistry. All other students who need a course in chemistry should be required to enroll in courses which will extend their knowledge base beyond what they already know. A class needs to be offered strictly for students who want to pursue a science or science-relate field and do not meet the requirements for admissions into the first general chemistry course.

The following are a few suggestions which may help to improve the teaching of a large-group lecture-oriented introductory chemistry course for the nonscience major student: (a) stress the conceptual aspects of the material as much or more than the algorithmic aspects, especially the understanding of new vocabulary; (b) carefully cover basic concepts at a rate appropriate for the novice learners enrolled; (c) decrease the amount of new subject matter presented per lecture; (d) allow class time for student interaction (i.e., encourage cooperative learning groups); (e) present well-organized lectures which stress the development of both algorithmic and conceptual problem-solving skills; and (f) maintain a classroom atmosphere which is conducive to learning chemistry in a relaxed, entertaining manner. Instructors must convey to their students an enjoyment of their chosen occupation, and let students know that they are there to help them learn about the wonders of the world through the study of chemistry. The use of a cooperative learning situation in this study proved to be a relaxed, student-centered experience which was positively rated by the students on their final evaluation of the course. Results from the "Course-Instructor Survey", administered to all students at the end of the semester and required by The University, indicated that 89% of the students enrolled in this course rated it as satisfactory or above.

Bersuker (1993) defined cooperation as the effect that one elementary act has on another. Even though this statement was made in reference to the chirality of molecules, it has relevance in today's classroom. Students are easily influenced by their perceptions of a course. Backart (1972) noted that if students believed that a particular chemistry course would somehow benefit them in the future, that there was an increased probability of success in that course. He also noted that students surveyed held a poorer attitude toward a class which was considered to take place in an impersonal atmosphere (characteristic of many large lecture sections). He suggested that teaching (e.g., lecture only) be revised, and that more emphasis be placed on topics relevant to the student, especially the nonscience major. These words are so easy to write, yet so difficult to implement. Money and faculty (whose main objective is teaching) are needed at the university level. Some universities are becoming more aware of these needs, and are proceeding to hire faculty whose primary interest is teaching and research in science education.

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