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ABSTRACT

Although students' misconceptions about the concept of chemical equilibrium has been the focus of numerous investigations, few have investigated students' systematic errors when solving equilibrium problems at the college level. Students (n=189) enrolled in the second semester of a first year chemistry course for science and engineering majors at a private university in New York State were studied to: (1) identify students' conceptual chemical errors and systematic mathematical errors when solving chemical equilibrium problems; and (2) to investigate the relationship between students' logical thinking ability and their performance on the kinetics and chemical equilibrium problems. Data was collected using a student demographics questionnaire, the Test of Logical Thinking, and students' responses to three chemical equilibrium problems and one chemical kinetics problem. Content analysis of the conceptual chemical and mathematical errors led to four conclusions: (1) students did not understand the relationship between experimental results and the rate of reaction; (2) students' misconception that an arithmetic relationship existed between concentrations of reactants and products led to a mathematical rather than a chemical solution to one problem; (3) many students seemed to have an overgeneralized definition of bases; and (4) students relied on using learned algorithms to solve problems. Contains 22 references. (MDH)

Students' Systematic Errors When Solving Kinetic and Chemical Equilibrium Problems

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Introduction

Many educational researchers (e.g., Fisher & Lipson, 1983; McDermott, 1988) assert that systematic errors provide important insights about students' thinking processes. Consequently, these insights may help teachers to design effective curricula and more productive remediation and teaching strategies.

Researchers investigated students' mistakes in three traditions. These are "Piagetian studies in the tradition of genetic epistemology, applications of the history of science in the tradition of conceptual change, and research on systematic error" (Confrey, 1990, P. 5). Science education researchers identified students' misconceptions about a variety of topics in physics, chemistry, biology, and earth science within the traditions of genetic epistemology and the history of science. The results of their investigations are now catalogued in several research reviews and bibliographies (e.g., Confrey, 1990; Eylon & Linn, 1988; Pfundt & Duit, 1985, 1988). Also, researchers have investigated and recommended strategies to correct students' science misconceptions using a variety of conceptual change teaching strategies (e.g., Anderson & Roth, 1989). In the tradition of systematic error, research flourished mostly in mathematics education and has focused on investigating students' procedural errors (Confrey, 1990). Recently, however, there has been published research on the conceptual basis for errors in mathematics (e.g., Resnik, Nesher, Leonard, Magone, Omanson, & Peled, 1989).

Research on misconceptions in chemistry has focused on such topics as the particulate nature of matter (e.g., Novick & Nussbaum, 1978; Gabel, Samuel, & Schrader, 1987), the mole concept (e.g., Cervellati, Montuschi, Perigini, Grimellini-Tomasini, & Balandi, 1982), the changes of state of water (e.g., Osborne & Cosgrove, 1983), solids and liquids (e.g., Stavey &

Stachel, 1985), acids and bases (e.g., Cros, Amouroux, Chastrelle, & Leber, 1986; Schmidt, 1991), and chemical equilibrium (e.g., Banerjee, 1991; Johnstone, MacDonald, & Webb 1977; Wheeler & Kass, 1978; Hackling & Garnett, 1985; and Camacho & Good, 1989). However, before the present interest in research on misconceptions, several research studies focused on identifying and correcting students' mistakes on chemistry examinations (e.g., Fensham & George, 1973; Kellett & Johnstone, 1974; Niedzielski & Walmsley, 1982).

Students' misconceptions about the concept of chemical equilibrium have been the focus of numerous investigations. The misconceptions identified in these investigations are presented in Table 1. Most of these studies were conducted at the high school level and a review of the literature identified a few studies investigating students' misconceptions and systematic errors when solving equilibrium problems at the college level.

Insert Table 1 About Here

Besides requiring knowledge of prerequisite chemical concepts, solving chemical equilibrium problems requires mastering many mathematical operations, and "the ability to deal with cognitive transformations associated with formal thinking ability" (Wheeler & Kass, 1978, p. 223). The concept of chemical equilibrium appears in most high school and college first year chemistry curricula and was identified by teachers as most difficult among several chemistry concepts (Finley, Stewart, & Yarrochi, 1982). Also, most of the research on students' errors on chemical equilibrium problems was either conducted abroad or with high school students. Consequently, it is important to identify the conceptual chemical errors and the systematic mathematical errors that students commit when solving chemical equilibrium problems at the first year college level. In addition, it is important to investigate the relationships between students' errors on chemical equilibrium and kinetics problems and their logical thinking abilities to identify possible causes for these errors.

Identifying students' conceptual and mathematical errors and understanding the relationships between these errors and students' logical thinking abilities may help teachers and curriculum specialists match curricula to the needs of college first year chemistry students. Additionally, communicating these findings to practitioners may help them realize the need to adjust their teaching to address the identified errors, and may encourage them to look more carefully at students' responses to discern new errors.

Consequently, the two main purposes of this study were 1) to identify students' conceptual chemical errors and systematic mathematical errors when solving chemical equilibrium problems; and 2) to investigate the relationship between students' logical thinking ability and their performance on the kinetics and chemical equilibrium problems.

Method

Subjects

Subjects for this study were 189 students (57.4% males and 42.6% females, average age 19.6 years) enrolled in the second semester of a first year chemistry course for science and engineering majors at a private university in New York State. Eighty-one and one-half percent of the students were white, 7.4% African-American, 6.8% oriental, 1.9% Spanish American, while 2.5% failed to report their race. Sixty-nine percent of these students graduated in the top 20% of their high school class. All students took at least one high school chemistry course while 25% took 2 or more courses.

Instruments and Procedures

The following instruments were used in the study:

a) Demographic Questionnaire. This questionnaire was used to collect information about such variables as sex, age, racial background, ranking in graduating high-school class, parents' educational backgrounds, and number and type of chemistry courses taken at the high-school level.

b) Test of Logical Thinking (TOLT). Developed by Tobin and Capie (1981), this instrument consists of 10 items (five groups of two items each) selected to measure several components of formal thought; these include proportional, combinatorial, probabilistic, and correlational thinking, as well as controlling variables. The 10 items of the TOLT contain two responses each - an answer and a reason for having selected the answer. Individuals must respond correctly to both components for the response to be considered correct. The TOLT has a reported internal consistency reliability coefficient of .84 and a value of .74 for this study.

Other sources of data for this study were the students' individual responses on one chemical kinetics and three chemical equilibrium problems on the final examination given during May 1990. The chemical kinetics problem was included in the analysis because the course instructor followed the conventional approach to teaching chemical equilibrium. In this approach, chemical equilibrium is explained in terms of kinetics rather than in terms of the "minimum of some potential, the Gibbs potential (G) or free energy of the reacting system" (Harris, 1982, p. 1034). Individual responses were important sources of data since students are encouraged to write down the steps and to show the mathematical manipulations they use in solving problems.

Students were asked to respond to the Demographic Questionnaire and the Test of Logical Thinking (Tobin & Capie, 1981) during their chemistry recitations sections in the first week of the 1990 Spring semester. Additionally, copies of individual students' final exams, given in May 1990, were obtained and photocopied during June 1990.

Data analysis

There were two types of data analysis used in this study. First, the problems were content analyzed to identify the types of conceptual and computational errors committed by the students. An initial set of students' answers were coded to establish the types of errors committed in each problem. Then the responses were read several times and the initial types of errors were modified and refined throughout the analysis to produce a final set of errors for each problem. Second, the correlations between students' performance on the kinetics and chemical equilibrium problems and their scores on the Test of Logical Thinking (Tobin et al., 1981) were computed to discern any possible relationships between these variables.

Description of the Chemistry Course for Science and Engineering Majors

Topics covered in the course included: chemical kinetics (rate laws and rate constants), equilibrium, pH of strong and weak acids, entropy, enthalpy, the spontaneity of reactions, the reactivities of metals, trends in the periodic table, electron configuration, the reactions of acids and bases, geometrical and optical isomerism, organic nomenclature, and nuclear chemistry. The instructor of the course uses the conventional approach in teaching equilibrium in which equilibrium is explained in terms of the kinetic "law of mass action."[1]

Students met three times per week. Two of these meetings were reserved for lectures by the course instructor. The third meeting, typically held on Fridays, was conducted by graduate teaching assistants who reviewed the week's topics and answered students' questions. The students were also involved in biweekly laboratory exercises on topics related to the lectures. Students' course grades were based on two one-hour-long exams, a cumulative final exam, and a laboratory grade.

Test Items and Results

The results of this study are presented as follows: the analyzed problem is presented followed by the conceptual chemical errors and the mathematical errors that were committed when solving the problem. This is followed by the results of investigating relationships between students' logical thinking ability, performance on the four problems, and course grades.

Problem 1:

For the reaction: $2A + 2B \longrightarrow$ Products

The following data were obtained from three experiments:

Experiment	[A], $mol.L^{-1}$	[B], $mol.L^{-1}$	Rate, $mol.L^{-1}S^{-1}$
1	0.22	0.22	0.816
2	0.44	0.22	3.26

[1]See Harris, W. (1982) for a critique of this approach to teaching chemical equilibrium.

3. 0.22 0.44 1.63

Use the data to answer:

a) What is the rate law for the reaction?

b) What is the numerical value of the rate constant?

Results:

Sixteen percent of the students used the stoichiometric coefficients in the equation provided in this problem to give the following rate law: Rate=k $[A]^2[B]^2$ when solving part **a** of the problem. Another 17% of the students attempted unsuccessfully to use the results of experiments 1, 2, and 3 to produce the rate Law. Students' responses show that they neglected to control variables when using the results of the experiments. For example, 16 students used the concentration of A in experiments 2 and 3 without apparently considering the fact that the concentration of B was different in the two experiments leading them to the following solution (Student 18):

For [A] $(.44/.22)^n=3.26/1.63$

$2^n=2$ therefore $n=1$

For [B] $(.22/.44)^n=.816/1.63$

$.5^n=.5$ therefore $n=1$

$R=K[A][B]$

An equal number of students committed a similar mistake by considering the concentration of B without controlling for the concentration of A.

Another type of error committed by 6% of the students involved taking 2A to be the concentration of reactant A in the rate law, resulting in answers such as $R=K\ [2A]^2[2B]$. A t-test for independent samples showed that there were significant differences between the TOLT scores of students who committed mistakes involving controlling variables and those students who answered this question correctly. Students who committed mistakes involving controlling variables scored significantly lower on the TOLT (t=2.16, Alpha=.03).

Students committed three main types of errors in part **b** of the problem. While 30% of the students were penalized for not providing units in their answers[2], 12% lost points for not squaring units during calculations, and approximately 3% calculated K for each experiment and averaged the resulting individual K's to calculate the required K. Most of the mathematical[3] errors committed in this part of the problem involved manipulating variables in the equation to reach a solution for K.

Problem 2:

K_C=4.4 x10^4 M^{-2} for the equilibrium given. What is the molarity of H_2 at equilibrium when the molarity of N_2 is 0.11 M and that of NH_3 is 1.5 M?

$$N_2\ (g) + 3\ H_2\ (g) \rightleftharpoons 2NH_3\ \ (g)$$

Results:

Approximately 8% of the students used an algebraic rather than a chemical approach to solving this problem. The following excerpt is a typical solution strategy used by students (Student 5)

> With 1.5 moles of NH_3, if we have .11M of N_2, we are left with 1.5 - 0.11=1.39 moles of H_2, since 1.39 is $3H_2$, then 1.39/3 is H_2, thus molarity is of H_2 is 0.463

Another typical algebraic solution used by students is the one provided by Student 21:

$$N_2\ (g) + 3H_2\ (g) \rightleftharpoons 2NH_3\ \ (g)$$

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[2]See Harris, W. (1982) for a critique of this approach to teaching chemical equilibrium and of the use of units when calculating K.

[3] In some cases the computational errors may be due to incompetence in using calculators, especially that students are encouraged to use one during examinations.

X 3X 2X

Since 1.5 moles of NH_3 is produced and it is 2x, then x=.75. Now H_2 is 3X, therefore molarity of hydrogen is 3 x .75=2.25.

Approximately 7% of the students made mistakes in setting up the mass action expression for the problem. These mistakes ranged from expressions that contained only the quantities given in the problem (for example $K_c=[N_2][NH_3]$), to problems with the coefficients in the expressions (Examples: $KNH_3]/[N_2][H_2]$ or $K_c=[N_2][H_2]^3/[NH_3]^2$). An additional 12% of the students lost points on the problem because they assumed that $Kc=4.4 \times 10^{-4}$ rather than 4.4×10^4.

Several students (17%) committed mathematical errors when solving this problem. These errors included mistakes in a) multiplying and dividing numbers containing scientific notation, b) calculating the cube root of a number, c) simple division and multiplication, and d) algebraic manipulations of the mass action expression.

Problem 3:

What is the pH of a 0.050 M solution of hypochlorous acid, HOCl?

$$K_a=3.0 \times 10^{-5} \text{ M}$$

Results:

There were three incorrect strategies used to solve this problem. In the first strategy, 14% of the students considered HOCl a weak base and used the following steps to solve the problem.

1. $HOCl \rightleftharpoons HO^- + Cl^-$
2. Calculate the number of moles of OH^- in solution using the following equality:

$3.0 \times 10^{-5} = X^2/.05$

3. Calculate pOH

4. Calculate pH from the equality pH+pOH=14.00

In the second incorrect strategy, 7% of students considered HOCl a strong acid and used the following steps to solve the problem:

1. $HOCl \rightleftharpoons H^+ + OCl^-$

2. Calculate the number of moles of H^+

3. Calculate pH

In the third incorrect strategy, approximately 30% of the students attempted to use the Henderson-Hasselbach equation to solve this problem. The first group of students (16%) eliminated the denominator in the following form of the equation: pH=pK - log [acid]/[base], possibly because there was no mention of base in the problem, then solved the problem using .05M as the concentration of the acid. The following is an example (Students 16 and 170) of how these students solved the problem:

pH=pKa -log [acid]/[base]   pH=4.5 - log [acid]

HOCl=.050M

pH=4.5 - log .050   pH=4.5+1.3=5.8

However, for a second group of students (11%), those who considered HOCl a base, the numerator was eliminated and the relationship became:

pH=pKa-log [acid]/[base]   pH=4.5+log [base]

HOCl=.050 M

pH=4.5+log .050   pH=4.5-1.3=3.2

Finally, a third group of students (approximately 4%) assumed that the concentrations of acid and base in the Henderson-

Hasselbach equation were the same, leading them to the conclusion that $pK_a=pH$:

$pH=pKa - \log [acid]/[base]$ $\quad$ $pH=pK_a - \log 0.05/0.05$

$pH=pK_a$, therefore $pH=4.5$

Approximately 16% of the students were unable to write the correct chemical equation for the problem. Most of the students in this group wrote the following equation: $HOCl \rightleftharpoons OH + Cl$, assuming that HOCl was a base, though the word "hypochlorous acid" was stated in the problem. The rest of the students used a variety of other equations including the following:

$HCl + 2H_2O \rightarrow 2HOCl + H^+$

$H_2O + Cl \rightarrow HOCl + H^+$

$2HCl + O_2 \rightarrow 2HOCl$

Very few students committed mathematical errors when solving this problem. These errors were limited to problems with a) multiplying small decimal numbers ($.050 \times 3.0 \times 10^{-5}$) and b) transforming the quotient to calculate the square root. For example, some students multiplied $.050 \times 3.0 \times 10^{-5}$ to get .0000015, but were unable to calculate the square root of this number to find the pH of the solution.

Problem 4:

Calculate the pH change that occurs when 0.5 mL of 0.10 M HCl (aq) is added to each solution:

a. Pure water

b. A solution that is 0.10 M CH_3COONa and 0.10 M CH_3COOH (aq).

Results:

Most of the students solved part **a** of the problem correctly.

However, those who did not, committed two types of conceptual mistakes. For example, 5% of the students considered HCl a weak acid with a K_a=1.8 x10-5, leading them to the following solution (Students 42 and 161):

$HCl \rightleftharpoons H^+ + Cl^-$

.05 X X

X^2/.05=1.8 x 10-5

X^2=9.5 x 10-4

X=3.08 x 10-2

pH=1.5

The second conceptual error involved the incorrect use of the Henderson-Hasselbach equation. Six students attempted to use this strategy to solve the problem. Students 16 and 126 provide an example of how this type of solution was accomplished:

Ka=1.8 x 10^{-5} pH=pK_a - log [acid]/[base]

pH=4.74 - log .10M HCl/.10 mL

pH=4.74 - log .10/.10 pH=4.74

Approximately 16% of the students were unable to identify the acid and the base when using the Henderson-Hasselbach equation in part b of the problem 4. The strategies that these students used show that they considered CH_3COOH a base. The responses of Students 12 and 186 illustrate the strategy used by these students (the students underlined the OH in CH_3COOH).

CH_3COO^-=Acid $CH_3CO\underline{OH}$=Base

.1 M - x .1 M + X

.1 M - .005 M=.095 M .1M + .005 M + .105 M

pH=pKa - Log [Acid]/[Base] pH=pKa - Log .095/.105

pH=4.75 + .04=4.79

Change in pH=4.79 - 4.75=.04

Five percent of the students did not seem to realize that the given solution was a buffer or that the equation

$$CH_3COOH \rightleftharpoons CH_3COO^- + H^+$$

represented a buffer solution in this problem. They seemed to think that it represented the ionization of a weak acid (CH_3COOH) (it is also possible that these students thought that the direction of ionization was always from left to right thus not really understanding the double arrow in the equation). Student 94's solution represents this type of solution:

$CH_3COOH \rightleftharpoons CH_3COO^- + H^+$

0.1

0.1 - X X X

$Ka=X^2 / 0.1 - X$ $X=0.1 \times 1.8 \times 10^{-5}$ X=.0013 M

pH=-log .0013=2.9

There were very few systematic mathematical errors committed in this part of the problem. The only errors detected were those involving division by decimal numbers and realizing that the logarithm of a number less that zero is negative. This last error was mostly committed with the conceptual error of thinking that CH_3COOH was a base. Consequently, the following steps appeared on 40% of the students who committed this error:

pH=pKa - Log .095/.105

pH=4.75 - Log .095/.105

pH=4.75 - log .090

pH=4.75 -.04

pH=4.71

Since the course was taught by one professor assisted by three teaching assistants (TA's), it can be argued that the TA's were not equally effective in working with the undergraduates in their respective sections, leading to the identified errors. To check this possibility, students' errors were broken down by TA (Table 2) and chi-square tests were used to determine whether the frequency of errors differed among the three TA's. The obtained chi-squares (one for each type of error) were not significant showing that the errors were distributed equally among the TA's.

Moreover, it can be argued that errors were functions of student achievement in chemistry with weak students committing significantly more conceptual errors than strong ones. To test this possibility, the frequency distributions of course grades and the errors per each grade were computed (Table 3). Chi-square tests were applied to the data to decide whether the frequency of errors differed among the different course grades. The obtained chi-squares (one for each type of error) were not significant showing that the distributions of errors and grades were not different.

Insert Tables 2 & 3 About Here

Relationships between students' logical thinking ability and their performance:

There were no significant relationships between students' performance on each problem and their performance on the Test of Logical Thinking (TOLT). Also, there were so significant relationships between the TOLT scores and the total grade on the four problems. However, there were significant relationships between the TOLT scores and students' performance on the final exam $r=.22$, $p<.01$) and TOLT scores and course grades ($r=.20$, $p<.01$).

Discussion and Conclusions

The following conclusions can be drawn from the analyses presented above. First, it seems that students did not understand the relationship between experimental results and the rate of a reaction (Problem 1). While many students were unable to control variables, many others did not find the given experimental results relevant and reverted to using the stoichiometric coefficients in writing the rate law. Second, many students thought that a simple arithmetic relationship existed between concentrations of reactants and products in problem 2 leading them to a mathematical rather than a chemical solution of the problem. Hackling and Garnett (1985) found that the students in their study committed a similar error. Third, as shown in problems 3 and 4, many students seem to have an overgeneralized definition of bases that asserts that "all substances that contain an OH are bases." Consequently, many of these students considered HOCL and CH_3COOH bases. On the other hand, while most students recognized HOCl and CH_3COOH as acids, they seem to have an overgeneralized definition of acids. This overgeneralization could be stated as follows "all acids ionize completely to produce $H^+(aq)$". This overgeneralization was evident when students considered HOCl a strong acid.

Fourth, it is obvious that there is an overwhelming emphasis on using learned algorithms, as equations and other memorized techniques, to solve the problems, sometimes without understanding the chemistry concepts involved in solving the problems. For example, at least 40% of the students wrote the Henderson-Hasselbach equation at the top of the page when solving problem 3. However, while many of them realized that the problem could be solved using a simpler method, a significant number attempted to use the equation to solve the problem. Another example where students used the Henderson-Hasselbach equation was problem 4b. However, because many of them could not identify conjugate acids and bases, they failed to solve the problem correctly. Thus they could activate the proper equation in their memory but they lacked the requisite knowledge to solve the problem. It seems that because students over rely on memorized equations they are successful when an equation can be applied directly to solve a problem but are less successful when they need qualitative chemical thinking to solve a problem. For example, although problem 4-b is more complex than problem 3, it can be solved by applying the Henderson-Hasselbach equation. Problem 3 on the other hand requires qualitative chemical thinking. Consequently, more students solved problem 4-b correctly than problem 3. Moreover, the fact that there were no significant relationships between students performance on the TOLT and their scores on the four problems could also suggest over reliance on algorithms. Students did not seem to be applying the formal thinking abilities to solve the problems and consequently no relationship could be found.

Finally, although these students were physical science majors, they committed computational and mathematical errors that should have been mastered at a much lower level, probably at the middle school and high school levels.

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Table 1.
Misconceptions in Chemical Equilibrium Identified in the Science Education Literature.

Author(s)	Subjects	Misconceptions
Johnstone, MacDonald, and Webb (1977).	Two hundred fifty five senior high school students.	a) Equilibrium consists of two independent and separate parts rather than one whole system. b) Students accepted equal and opposite rates only superficially and were confused when asked to interpret the reversed arrow convention when the forward and reversed arrows are of unequal length. c) Increased pressure due to heating alters the composition of a mixture in such a way to reduce the pressure d) Catalysts have no effect on or decrease the reverse rate in an equilibrium reaction.
Wheeler and Kass (1978).	Ninety-nine 12th grade students.	a) Inability to distinguish between mass and concentration b) Inability to distinguish between how fast a reaction proceeds (rate) and how far (extent) the reaction goes. c) Uncertainty as to when the equilibrium constant is in fact a constant. d) The application of Le Chatelier Type reasoning in inappropriate situations e) Inability to appreciate that certain substances display a fixed or constant concentration in certain chemical reactions. f) Inability to consider all possible factors affecting the equilibrium condition of a chemical system.
Hackling and Garnett (1985).	Thirty 12th grade students.	a) The rate of the forward reaction in an equilibrium reaction increases as a function of time. b) A simple arithmetic relationship exists between concentrations of reactants and products. c) When a system at equilibrium is changed, the rate of the favored reaction increases but the rate of the other reaction decreases.

Camacho and Good (1989)	Twenty three subjects (5 high school, 8 under-graduate, 6 Doctoral students, and 4 faculty)	a) Novices showed knowledge gaps about the taxonomy of chemical equilibrium constants. b) Most novices neglected the fact that only temperature can change the value of the equilibrium constant. c) Almost all novices did not distinguish between how fast a reaction proceeds (rate) and how far (extent) the reaction goes.
Banerjee (1991)	One hundred and twenty science education undergraduate students and 69 school teachers in India	a) Students and teachers do not appreciate that the use of Le Chatelier's principle is limited to qualitative information. b) Students and teachers believe that a large equilibrium constant implies a very fast reaction. c) Students and teachers think that there is no Hydrogen ions in a solution of sodium hydroxide or in distilled water.
Schmidt (1991).	Seven thousand five hundred German high school students	a) Students assumed that neutral solutions are formed in all neutralization reactions, even if a weak acid or a weak base take part in the reaction. b) Students believed that all neutralization reactions are irreversible reactions

Table 2.
Percent Student Errors on Each of the Problems as a Function of Teaching Assistants (TA's)

TA	Problem 1-a	Problem 1-b	Problem 2	Problem 3	Problem 4-a	Problem 4-b
1	35	31	34	32	33	31
2	32	40	29	35	35	33
3	33	29	37	32	32	36

Tested at the .01 level of significance

Note: The expected frequency was calculated based on the number of students each of the teaching assistants had in their respective sections.

Table 3.
Percent Student Errors on Each of the Problems as a Function of Course Grades.

Course Grade	% in Grade	Problem 1-a	Problem 1-b	Problem 2	Problem 3	Problem 4-a	Problem 4-b
F	11	11	12	17	15	14	14
D	12	14	12	17	15	13	12
C	61	67	60	58	62	60	62
B	14	7	15	8	6	12	10
A	2	1	1	0	1	1	2

Tested at the .01 level of significance

Note: Since a number of the cells contained frequencies of less than 5, the chi-square could become too liberal -- that is significance is found when there is none. However, no significance was found and thus this should not be problematic).