PART I: BACKGROUND

Title: Exploring Students' Understanding of the Relationship Between Acid-Base Conjugate Pairs and Their Relative Strength

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Course Name: General Chemistry II

Course Description:

General Chemistry II (CHM 104) is the 2nd course in a two semester sequence of introductory chemistry. It is a mandatory course for students requiring 1 year of chemistry for their program. Students typically complete the General Chemistry I (CHM 103) and II sequence in the first two semesters of their freshman year if they meet the math pre-requisite. CHM 104 significantly broadens student understanding of fundamental chemistry concepts, and the laboratory component of the course has been designed to provide students with hands-on experience with challenging theoretical concepts. This lesson study focuses on the course's 5th laboratory experiment, *Acids and Bases I: Properties of Acid and Base Solutions,* which is the first experiment dealing with acid/base chemistry. Experiment 5 is followed by two more experiments that explore buffer systems and acid/base titrations, both of which build on the basics that are covered in Experiment 5.

Abstract:

During our time working with students in CHM 104, we have observed that concepts related to acid-base equilibrium are particularly challenging for students. Even after a significant amount of lecture and laboratory instruction, students still appear to have only a superficial understanding of the topic at the completion of the course. Therefore, the main goal of this study was to improve students' understanding of the relationships between acids and bases and their conjugates, one of the most fundamental aspects of acid-base chemistry. This goal was approached by modifying the first lab experiment to deal with acid-base chemistry (Experiment #5). Students typically arrive to a lab period having skimmed the experiment procedure at best. Therefore, the instructor spends a significant amount of instruction time (~45 min) discussing the theory behind the experiment, as well as practical aspects of the lab. By removing the bulk of the pre-lab instruction out of the set experiment time (3 hours), and also asking students to complete work before they attended the lab, we hoped to focus their attention to the outcomes of the experiment having come to lab more prepared than in the past. Through this lesson study we found the modifications made to the experiment were useful in allowing the students to demonstrate their proficiency with equation writing skills, and also reinforced their understanding of many of the differences between acids and bases. However, common misunderstandings surrounding pK_a, pK_b, and pH we not fully addressed and still need some attention.

PART II: THE LESSON

Learning Goals:

Upon completion of Experiment 5, students will be able to:

1. Explain the following concepts:
   (a) The relationship between K_a and K_b, and acid/base strength – this is achieved by using a video presentation along with the written procedure in the lab manual which show how pH differs for acids and bases and their conjugates.
   (b) The qualitative differences in the behavior of weak/strong acids and bases – this is achieved through the pH measurements of known weak/strong acids and bases

(c) How strong acids or bases have weak conjugates – this is achieved by examining the pH values of known acid/base conjugate pairs.

2. Perform the following skills:
   (a) Write out a balanced equation for the reaction of acids/bases with water – this is achieved by having the students write balanced equations for every acid/base reaction that they perform in the experiment.
   (b) Calculate the concentration of acids/bases from measured pH – this is achieved by having the students perform this calculation for a strong acid and a weak acid.
   (c) Calculate the K_a/K_b for an acid/base from the conjugate K_a/K_b - this is achieved by explaining the relationship between K_a/K_b and K_w .
   (d) Use a pH meter – this is achieved by having the students calibrate and use a pH meter for the duration of the experiment.

Lesson Plan

Students begin this lesson by watching an online video created specifically for this lab. The video should be made available to the students one week preceding this experiment. Instructors should be prepared to send out at least one reminder. If the video link is provided within the course management software (e.g., D2L), instructors can potentially track who has viewed the video. The video discusses the fundamentals of acids and bases, how to identify whether a compound is an acid or a base, and how pH is used to determine the relative strengths of acids and bases. The direct link and embed code are provided below.

LINK:

http://youtu.be/qRsbBxYoxcI

EMBED:

<iframe width="560" height="315" src="http://www.youtube.com/embed/qRsbBxYoxcI" frameborder="0" allowfullscreen></iframe>

At the start of the lab period, students completed a pre-lab quiz (Appendix A) to assess what they have learned by watching the video and reading through the experiment procedure. Roughly 20 minutes should be allocated for the quiz, although students may finish much earlier.

With our implementation of the lesson, students were also asked to arrive at the lab having completed the first section of Part A (see Appendix B), which requires that they use knowledge gained from the video and the information provided in the procedure introduction to complete a table ranking unknown acids and bases in order of decreasing acidity given K_a and K_b values, and calculate the expected pH for solutions with a concentration of 0.10 M. This table can also be completed at the start of the lab period if preferred, and at least 45 minutes should be allotted. If the latter approach is taken, students can work in pairs. One can also arrange the students in larger groups to discuss their choices. If this exercise is completed ahead of time, the first 45 minutes of the lab time can be used to go through the students' answers as a group and point out common pitfalls. Instructors should give at least one example of the correct way to calculate pH from concentration and K_a or K_b, how to measure pH, and how to calculate percent ionization. It is also important to go through the procedure for calibrating the pH meters for the second part of the lab. The full text for the lesson, including data sheets, is provided in Appendix B.

The second section in Part A requires students measure the pH of known 0.10 M acid and base solutions. The instructor should ensure that these solutions have been properly made and tested for accurate pH. For our set up, each student pair used a wooden rack containing six 20-mL beakers. The beakers should be filled only to the 10 mL mark as they can overflow if there is more solution in them when the pH meter is inserted. Once the pH of each solution has been measured, the students compare the measured pH values to those they calculated prior to coming to lab. Students must also write the balanced equation for the compounds' reaction with water to form either the hydronium ion and a conjugate base, or the hydroxide ion and a conjugate.

For the sodium chloride solution, which should have a pH of ~7.00, the compound's reaction with water should be represented by the autoionization of water due to the fact that water's autoionization is the reaction influencing the pH in the solution; neither the sodium nor the chloride affect the pH. **This is a very common point of confusion for the students, so a discussion of this can be done to the whole group at this point.**

For Part B of the lab, students measure the pH of acetic acid and hydrochloric acid solutions of unknown concentration, and then determine the concentration of the solutions based on the pH they measured. Instructors should have the molarities of the solutions determined beforehand. For our experiments, we used solutions with a target concentration of ~0.250 M for acetic acid and ~0.025 M for hydrochloric acid. These solutions are standardized and accurate molarities are sent out to instructors each semester, along with the average pH measurement for each solution.

At the end of the experimental portion of this lab, there are four assigned problems. If there is time at the end of the lab period, instructors could have the students begin to answer these problems, or they can be assigned as take home problems to be submitted at a later date.

With our lesson study, students had to complete a post-lab quiz once they had finished filling out their experiment datasheets. This post-lab quiz was identical to the pre-lab quiz taken at the start of the lab period. Having the post-lab quiz is not necessary for teaching this experiment unless instructors are interested in assessing how much knowledge students had gained during the session.

PART III: THE STUDY

Approach:

Observations were collected by at least two instructors in the lab who walked around and listened to the students in their discussions with each other and the instructor. The pre- and post-lab quizzes were also designed to assess the students' level of knowledge before and after the experiment was performed.

Findings/Discussion:

Using the pre- and post-lab quiz as an assessment instrument (Appendix A), we observed that the majority of students (56%) were able to correctly predict whether an acid or base was weak or strong based on its K_a or K_b (Fig. 1, first bar; Quiz question #1) before the lab session began. In fact, the only major student error on the pre-lab quiz was mistaking acetic acid for a strong acid based on pK_a (which may simply be due to uncertainty about the weak/strong cutoff point). Since most of the remaining students (39%) responded correctly to this question after participation in the lab, **it appears that learning objective #1 has been fairly well addressed before the start of lab for many students, and the lab appears to reinforce the concept for the remainder.**

Most students (72%), also appear to be entering the lab session with a relatively strong ability to write out balanced equations for the reaction of acids and bases with water (Fig 1., second bar; Quiz question #2). However, 28% of students were observed to decline in ability on the post-lab quiz. Since this decrease was primarily due to missing charges on equilibrium species, we believe students may have forgotten to complete the expressions due to their hurry to be done with the lab session. As such, it appears that **decreases in student performance on skill #1 may be more a reflection of how the assessment was performed (i.e. given in a context where students were more careless with the post-assessment) rather than a substantial decrease in student understanding.**

Unlike the first two learning objectives, only a minority (17%) of students could correctly select the pH of a solution for the conjugate base of a weak acid on the pre-lab quiz (Fig. 1, third bar; Quiz question #3). Some students (22%) did answer the question correctly after the lab period; however, the majority of students decreased (28%) or showed no change in ability (33%). The reason for the decrease in performance is unclear. It may be that some part of the lab session inadvertently reinforced a common misconception about pH (i.e., that the sum of the pH values of conjugates is equal to 14, which is a false transfer from the relationship of pK_a and pK_b). In summary, **it appears that this laboratory session did**

not help most students improve their understanding of objective #3, and that adjustments to the lesson are still required to address this concept.

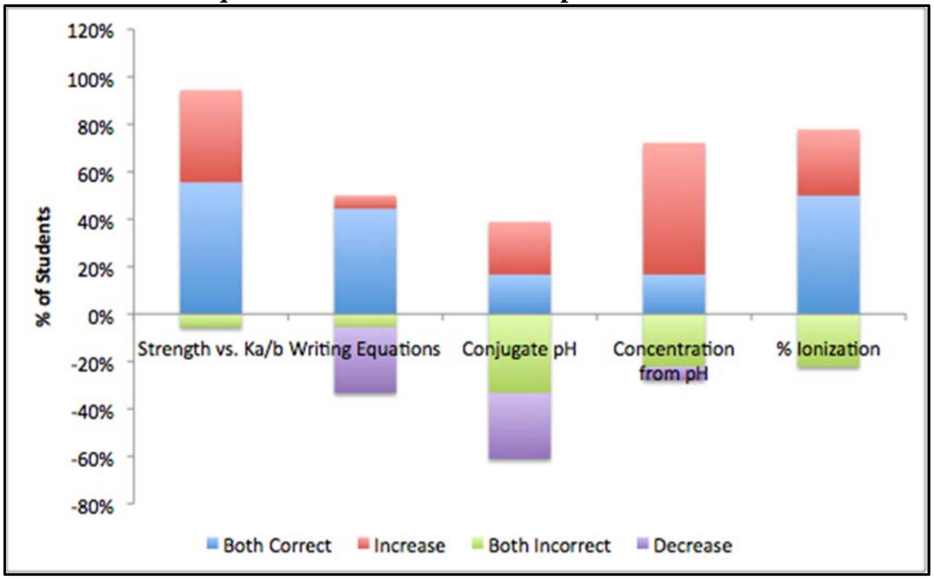

Figure 1: Changes in Student Pre/Post-Responses on Assessment Instrument for Spring 2013

Overall, the lab session appears to have had a significant, positive effect on students' ability to calculate the total concentration of a weak acid and its percent ionization from pH (Fig. 1, bars 4 and 5; Quiz question #4). We believe that this is most likely the result of having to solve a similar problem as part of the lab. In this environment, students are able to receive immediate feedback and guidance during the problem-solving process.

Despite some significant improvements, certain important conceptual issues were still observed in student responses. The two most common errors were mistakenly providing the value for the hydronium ion concentration, or the value for the final equilibrium concentration of the protonated acid (Fig. 2; Quiz question 4). This suggests that students may not have had a strong understanding of the conceptual framework surrounding the question, and were simply performing familiar algorithms. Similarly, while a surprisingly large percentage of students used the correct functional form when solving question part 4b in both the pre- and post-lab quizzes, most used their incorrect values from the previous answer to compute the answer, implying that they may be simply plugging values into a memorized equation. Nevertheless, we observed differences in pre- and post-responses that imply most students are making progress towards greater conceptual understanding. In particular, the percentage of students calculating the hydronium ion concentration incorrectly decreased significantly (27% down to 17%), while the percentage of students calculating the final equilibrium concentration of the protonated acid increased from 17% to 27%. These improvements stemmed from students who had previously provided weaker answers, implying a progression towards more conceptually sound understanding. Thus, **it appears that this lab session did significantly increase students ability to perform skill #3, but that there remain opportunities for improvement in conceptual understanding.**

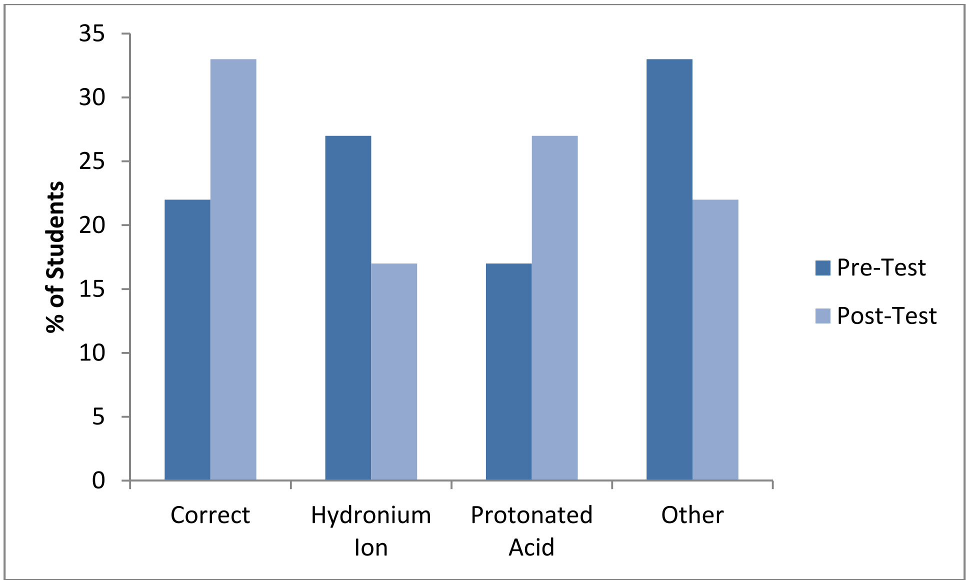

Figure 2: Conceptual Changes in Student Responses to Assessment Question #4a.

Conclusions:

From this work is appears that students already understood or gained understanding of the relationship between K_a/K_b. Also, students were strong at writing out equations; however, rushing at the end of lab increased errors within their post-lab quizzes. Most students still struggled with understanding the relationship between conjugate pH values even after the lab session. The students' ability to calculate weak acid concentration and percent ionization from pH showed improvement, but their conceptual understanding of these calculations could still be improved.

Recommendations:

We feel that continued work on a way to make students think critically about the conjugate pH concept is needed. Another point of investigation would be to find ways to strengthen students understanding of what each equilibrium species is and how they relate to one another. We would recommend keeping the pre-lab exercise, as it seems to help with the calculations in lab. Our final version of the pre-post quiz does not ask students to distinguish between weak and strong acids when calculating concentration. Since many students do not appear to have initially recognized how these differences affect the calculation of concentrations from pH during the lab session, this may be something to change in future versions of the assessment.

Appendix A

CHM104 Pre (Post) -Lab Test Name______________________

1. Predict which acids will be strong/weak based on pK_a. (1.5 pt)

	pK_a	Strong or Weak?
Acetic Acid	4.75	
Ammonium ion	9.25	
Hydrochloric Acid	Less than 1	

2. Predict the reaction equation for:
   (a) a base (NH_3) reacting with water (0.5 pt)

   (b) an acid ($HC_2H_3O_2$)reacting with water (0.5 pt)

3. A 0.100M weak acid solution has a pH of 6.3. What might you expect the pH of a 0.100M solution of the conjugate base to be? (0.5 pt)
   (a) pH = 7.7
   (b) pH = 12.3
   (c) pH = 3.1
   (d) pH = 6.3
   (e) pH = 14.0

   Briefly explain your answer. (0.5 pt)

4. An unknown concentration of lactic acid ($K_a = 8.3 \times 10^{-4}$) has the pH of 2.80.
   (a) What is the concentration of lactic acid in this solution? (1)

   (b) What is the percent ionization for the weak acid? (0.5)

Appendix B
Acids and Bases I: Properties of Acid and Base Solutions

In this experiment you will explore the fundamental relationships of solutions that contain acids and bases, by measuring the equilibrium concentration of H_3O^+ ions in an aqueous solution. This is one of the easiest properties to experimentally measure in the lab, by using a pH meter. Measurement of pH will be used throughout the next several weeks to characterize properties of aqueous solutions. The conversion between pH and $[H_3O^+]_{eq}$ is given by Eq. 1.

$$\text{pH} = -\log[\text{H}_3\text{O}^+]_{\text{eq}} \qquad (1)$$

Objectives

Use pH measurements to:

Part A: Determine the relationship between the strength of an acid and the strength of its conjugate base.

Part B: Calculate the concentrations of a weak acid solution and a strong acid solution.

Equilibria for acids and bases: The three important equilibria for solutions that contain acids and bases, K_a , K_b , and K_w, are defined below. An important relationship between these equilibria for a weak acid and its conjugate base is that $K_a \times K_b = K_w$.

1. Weak acid (HA) reacting with water (K_a). The strength of an acid is characterized by K_a. A larger K_a indicates an acid that is capable of generating more H_3O^+ by reacting with water.

   $HA_{(aq)} + H_2O_{(l)} \leftrightarrows A^-_{(aq)} + H_3O^+_{(aq)}$ $\qquad K_a = \dfrac{[A^-]_{eq}[H_3O^+]_{eq}}{[HA]_{eq}}$

   ↑ acid ↑ conjugate base

2. Weak base (A^-) reacting with water (K_b). The strength of a base is characterized by K_b. A larger K_b indicates a base that is capable of generating more OH^- by reacting with water.

   $A^-_{(aq)} + H_2O_{(l)} \leftrightarrows HA_{(aq)} + {}^-OH_{(aq)}$ $\qquad K_b = \dfrac{[HA]_{eq}[OH^-]_{eq}}{[A^-]_{eq}}$

3. Autoionization of water (K_w)

   $H_2O_{(l)} + H_2O_{(l)} \leftrightarrows H_3O^+_{(aq)} + {}^-OH_{(aq)}$ $\qquad K_w = [H_3O^+]_{eq}[OH^-]_{eq} = 1.00 \times 10^{-14}$

Many properties can be calculated from pH measurements. For example, the concentration of a weak acid ($[HA]_0$) solution can be obtained from measurement of pH, if the K_a value for the acid is known, by using an equilibrium table as shown below.

	$HA_{(aq)}$	+	$H_2O_{(l)}$	$\leftrightarrows$	$A^-_{(aq)}$	+	$H_3O^+_{(aq)}$
Initial conc.	$[HA]_0$				0		0
Change in conc.	-x				+x		+x
Equil. Conc.	$[HA]_0$- x				x		x

$$\ldots\quad K_a = \frac{x^2}{[HA]_0 - x}$$

The '**x**' can be obtained directly from the pH measured from the solution, leaving $[HA]_0$ the only unknown.

Additionally the percent ionization can be calculated. The percent ionization for an acid describes the amount of acid in its dissociated form and is given by Eq. 2, where $[HA]_0$ is the initial concentration of the acid in the solution.

$$\%\ \text{ionization} = \frac{[A^-]_{eq}}{[HA]_0} \times 100 \qquad (2)$$

The $[A^-]_{eq}$ can be obtained from the ICE table on the previous page.

Procedure

Obtain from the stockroom a pH meter (keep it in the storage solution when not in use) and a rack with six 20-mL beakers.

Part A:

> **PRE-LAB:** Complete the top table on the data sheet. Given the K_a/K_b values for the unknowns listed, calculate the pH and % ionization of these acids or bases. Rank the unknowns from most acidic (1) to most basic (7). Identify which pairs of solutions are conjugates to one another.

In this part of the experiment, you will measure the pH of several solutions containing acids or bases. Your objective is to determine the relationship between the strength of an acid and the strength of its conjugate base.

1. Calibrate a pH meter using the instructions provided by your lab instructor.

2. Measure the pH of the following solutions: acetate anion, acetic acid, ammonium ion, ammonia, hydrochloric acid, sodium chloride, and sodium hydroxide. Record these values in your data table. Assume all solutions are 0.10 M in concentration. Rinse the glass electrode on the pH meter with deionized water briefly between each measurement.

3. Write out the reaction that occurs for each acid or base with water. Based on the relative pH measurements of these solutions, compare to the calculated values and determine the unknown identity.

Part B: Your instructor will give you an acetic acid solution and a strong acid solution. Measure the pH of each solution. Use the measured value of pH and the value of K_a for acetic acid (1.85×10^{-5}) to calculate its concentration. Use the measured pH for the HCl solution to determine its concentration (assume 100% ionization).

Questions:

1. Butanoic acid (HC_4H_7O) has a K_a value of 1.51×10^{-5}.
   (a) Write an equation to show how this acid dissociates in water and identify its conjugate base.
   (b) If you measured the pH of two solutions, one containing 0.100 M butanoic acid and one containing 0.100 M of the conjugate base, what will their respective pH values be?

2. If a solution of HF ($K_a = 6.8 \times 10^{-4}$) has a pH of 3.65, calculate the initial concentration of the acid solution.

3. Using a pH meter, the pH of a cranberry juice cocktail was found to be 2.46, which indicates that the [H_3O^+] is 3.47×10^{-3} M. Titration of a 1.0-mL sample of the juice to approximately pH 7 required 0.94 mL of 0.10 M NaOH, indicating a total acid content of 0.094 M. Give a plausible explanation for why these two numbers don't agree.

4. Nicotinic acid, $HC_6H_4NO_2$, is found in minute amounts in all living cells, but appreciable amounts occur in liver, yeast, milk, adrenal glands, white meat, and corn. One gram (1.00 g) of the acid dissolved in 60 mL of solution gives a pH of 2.70. What is the approximate K_a value for the acid?

Name:_______________________ Lab Section:_______ Partner:_____________________Date:_______

Part A:

Unknown	K_a or K_b	Rank the unknowns from most acidic (1) to most basic (7)	Calculated pH of 0.10 M solution	% Ionization (Calculated)	Proposed Conjugate (A – G)
A (acid)	$K_a = 1.8 \times 10^{-5}$				
B (acid)	K_a = >> 1				
C (acid)	$K_a = 5.8 \times 10^{-10}$				
D (base)	>> 1				
E (base)	1.8×10^{-5}				
F (base)	5.6×10^{-10}				
G (base)	<< 1				

What do your observations tell you about the relationship between the strength of an acid and the pH of the solution?

What do your observations tell you about the relationship between the strength of an acid and the strength of its conjugate base?

Unknown	pH (measured)	Unknown Identity	Reaction that produces H_3O^+ or OH^-
acetic acid ($HC_2H_3O_2$)			
sodium acetate ($C_2H_3O_2^-$)			
Ammonia			
ammonium chloride			
hydrochloric acid			
sodium chloride			
sodium hydroxide			

Part B:

Acetic acid pH: ____________ Concentration of acetic acid: ___________

HCl pH : ____________ Concentration of HCl: ___________

Show your strategy (including calculations) used for determining concentration of the acetic acid and the HCl: