PART I: BACKGROUND

Title: Exploring Students' Understanding of Acid/Base Buffers in a Laboratory Setting

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Course Name: General Chemistry II Laboratory

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 who are required to have one year of chemistry in 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 prerequisite. CHM 104 significantly broadens student understanding of fundamental chemistry concepts and, unlike CHM 103, builds on topics throughout the semester. As a result, students often have difficulty with the course since a misunderstanding can carry through to multiple topics. Students also often have difficulty connecting material they learn in lecture with the hands-on experiments they perform in the laboratory, especially related to the equilibrium and acids/bases chapters.

This lesson study focuses on the CHM 104 course's 6th laboratory experiment, *Acids and Bases II: Preparing and Using a pH Buffered Solution*, which is the second experiment dealing with acid/base chemistry. Experiment 6 is preceded by an introductory lab to acids and bases that was featured in a previous lesson study undertaken by Drs. Turov and Friesen along with colleagues Dr. Melissa Anderson and Dr. Nadia Carmosini and is followed by an experiment that explores acid/base titrations.

Abstract:
After the successful redevelopment of Experiment 5 in a previous lesson study, it gave us the opportunity to revisit the next experiment in this acid/base series and work on improving student understanding of buffers, a challenging topic for most students in CHM 104. Though students are usually able to complete the relevant calculations for buffers in lecture, they generally are lost in a laboratory setting when they need to perform the relevant calculations and actually prepare a buffer on their own. A significant portion of the laboratory period is spent on describing buffer preparation and calculations; however, students still seem confused by the procedure and need quite a bit of assistance with the calculations. For this lesson study, we have prepared pre-lab videos that showcase the preparation of the buffer and also streamlined the experiment to only focus on one type of buffer system, which has helped shorten the pre-lab lecture and alleviated some confusion about preparation. We also found that a modified data sheet allowed the students to guide themselves through the calculations and also helped them relate their thought process to the material they learned in lecture. We are still working on ways to help students bridge the gap between experiment and calculations.

PART II: THE LESSON

Learning Goals:

Upon completion of Experiment 6, students will be able to:

1. Explain the following concepts:
    a. What a buffer is and what its uses are.
    b. How to select a buffer system given a target pH value.
    c. How buffers resist changes in pH upon addition of acid or base.
    d. The relationship between K_a, pK_a and the Henderson-Hasselbach equation.

2. Perform the following skills:
    a. Prepare a buffer solution.
    b. Use the Henderson-Hasselbach equation effectively.
    c. Apply ICE and BCA tables appropriately.

Lesson Plan

Students are expected to have read through the experiment procedure (Appendix A) and to have watched a series of videos that go through the calculations they would be completing in the experiment. There is also a video that demonstrates the lab techniques they need to complete the practical portion of the experiment. These videos are made available to the students at least one week prior to the experiment. If the video link is provided within the course management software (e.g., D2L), instructors can potentially track who has viewed the videos.

At the start of the lab period, students complete a pre-lab quiz (Appendix B) to assess what they have learned by watching the videos and reading through the experiment procedure. Roughly 20 minutes can be allocated for the quiz, although many students will finish the quiz much earlier.

Once the quiz is complete, the instructor briefly reviews what was covered in the videos and begins to go through the example calculations for setting up a buffer solution and calculating the pH once a strong acid or strong base is added (Appendix A). Figure 1 shows the instructors board notes from the Spring semester observed session. At this point, the students begin the practical portion of the lab and calculate the ratio of acid to conjugate base they need to achieve their assigned buffer pH. They prepare a concentrated buffer and a diluted buffer from the ratio information and test their capacities by adding low concentrations of a strong acid and a strong base to small volumes of each buffer. The students record all pH measurements so that they can be compared to their calculated pH values, which they complete after the practical portion of the lab has been concluded. It is at the lab instructor's discretion as to when these calculations should be submitted. As there are no official assigned problems with this lab at the moment, many instructors allow students to complete these calculations outside of the lab for submission the following week. With our study, students were encouraged to remain in the lab after they had completed their measurements so that they could complete these calculations before leaving and have the instructor answer any questions that arise.

For the completion of the lab in our study, students had to complete a post-lab quiz identical to the pre-lab quiz they had at the beginning of the session. Having the post-lab quiz is not necessary for teaching this experiment unless instructors are interested in assessing how much knowledge students have gained during the session.

PART III: THE STUDY

Approach:

Observations were collected by 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 each student's level of knowledge about buffer selection, preparation and strength before and after the experiment was performed.

Findings/Discussion:

Using the pre- and post-lab quiz as an assessment instrument (Appendix B), we observed that students showed improvement over the course of the experiment - the average increased from 3.1/4 to 3.6/4 in the Spring 2015 observed lab section and from 3.4 to 3.8 in the Fall 2015 observed lab section.

In Fall 2014, 55% of the students received a perfect score in the pre-lab assessment and then 80% received a perfect score in the post-lab assessment. In Spring 2015, just 39% received a perfect score in the pre-lab assessment and 67% scored perfectly in the post-lab assessment. This indicates a thorough understanding of the basic ideas. It appears the Spring 2015 semester students were coming to lab less prepared than the Fall students based on the lower assessment scores. Despite this, the Spring lab section almost doubled in the number of perfect scores in the post-lab assessment, indicating that the experiment was an effective lesson on the fundamentals of buffers.

Question 1, addressing the fundamental objective of defining the term "buffer" indicated that most students understand this concept, as 85% of the students in Fall and 68% in Spring answered correctly both on the pre- and post-lab assessment. In Fall 2014, students who answered incorrectly initially fixed their errors on the post-lab assessment. Conversely, in Spring 2015, while there was some improvement, we also saw a small number get the question wrong after previously answering correctly. Perhaps this is a result of trying to go through the post-lab assessment too quickly and not thoroughly reading the question options. These results indicate that most students understand this concept and it is cemented when the instructor defines the term "buffer" during the discussion of the experiment.

From the assessment, it is clear that question two proved difficult for students, as this question had the fewest correct responses on both the pre- and post-lab assessment. This question is fundamental to the understanding of buffer problems, but this concept (how to choose a buffer system) is not clear to students before doing the experiment. We can conclude that students are not connecting with the concepts/learning goals of the experiment, and are focusing much more on the calculations necessary for the experiment. However, after performing the experiment, all of the students in the Spring section (and most in the Fall section) who had gotten the question wrong initially then answered correctly in the post-lab assessment. It seems that the experiment is sufficient for students to understand this concept.

In question three, addressing the important idea of buffer strength relating to concentrations of weak acid and base, in both sections, we saw incorrect answers that carried over into the post-lab assessment. This indicates that the experiment does not completely clear up misconceptions about how buffer strength is determined. It would be worthwhile to add a question to the experiment that requires students to directly compare the moles of the components of the buffer to the change in pH.

Question 4 demonstrated that the experiment was effective for understanding the Henderson-Hasselbalch equation, one that is central for buffer calculations. In the Fall section, students came in with a solid understanding of this concept and everyone answered correctly both in the pre- and post-lab assessments. In the Spring section, fewer students received perfect scores on this question, but improved by 21% in the post-lab assessment, with only 5% (1 student) decreasing in score. This indicates that students have a good understanding of this topic from lecture, and this is improved by the experiment.

NOTE: All statistics are shown below in Figure 2.

A shortened procedure and updated data sheet were given to the students (Appendix A), which also seemed helpful for guiding the students through their procedure and calculations. Typically, students are given a long introduction and told about two different buffer systems; here, we moved to only one system so all of the students were working with the same chemicals and calculations, which eased the workload for both students and instructor. Students were able to check off each item on the procedure list (which matches the steps outlined in the online instructional video the students watch) and then perform the indicated calculations. The data sheet also asks the students to write balanced equations for what’s occurring in the buffer, which seems to help guide their understanding for each step of the experiment. Overall, students worked fairly independently and there were only minor incidences of needing to be corrected by the instructor (mostly just questions concerning equipment use).

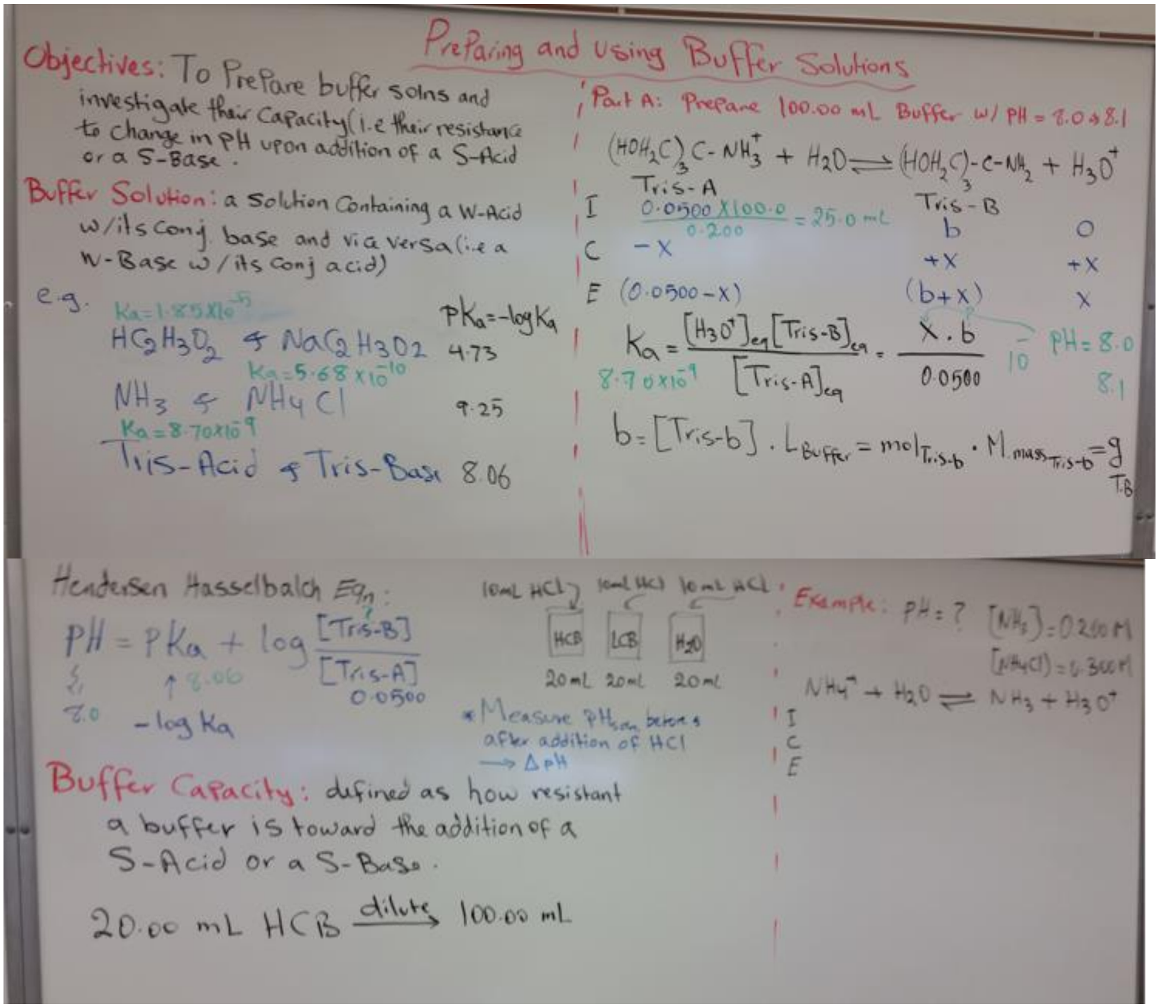
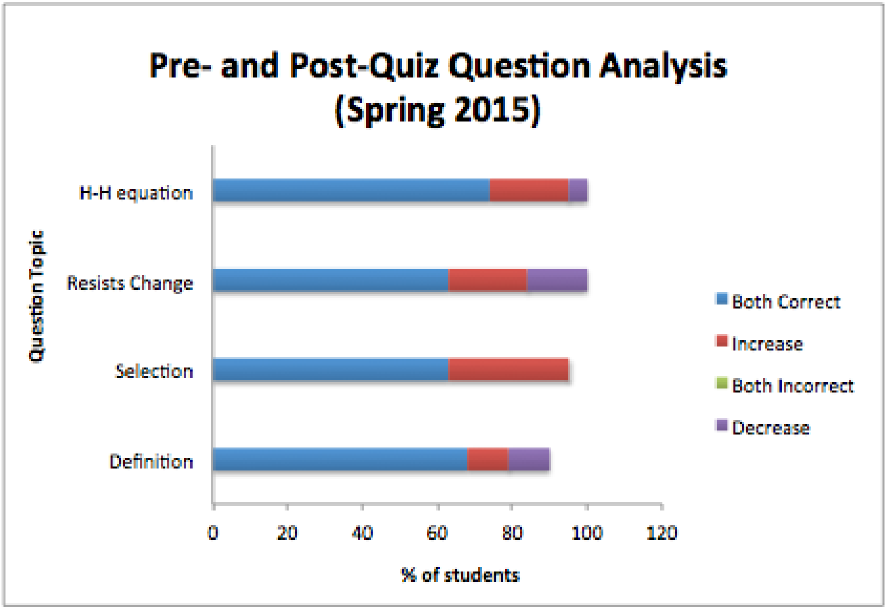


Figure 1. Buffer background information and calculations outlined in the pre-lab discussion.



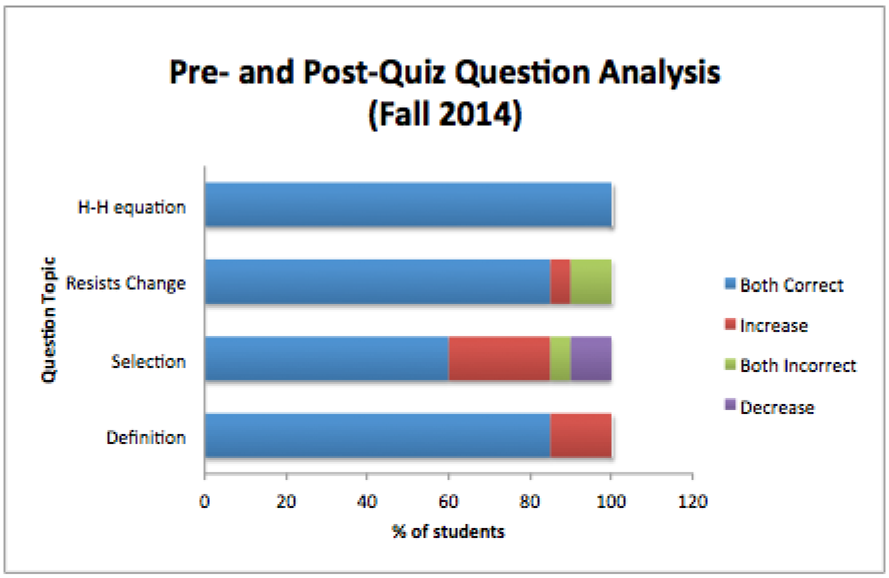


Figure 2: Changes in Pre/Post Lab Assessment in Observed Sections.

Conclusions: As a result of this lesson study, we noted more independent work from the students than we had seen in previous sections and a decrease in questions related to the procedure and necessary calculations. However, the performance from the assessment indicates that there is still a disconnect between the conceptual ideas/learning goals of this experiment and the practical aspects of preparing a buffer and performing relevant calculations. As a result, more work should be done to highlight the important learning goals for this experiment.

Recommendations: The department's laboratory manual should incorporate the updated procedure and data sheets used in this study. There should also be an effort made to provide a <u>short</u> introduction to buffers, specifically related to the learning goals for this experiment. Laboratory instructors should also try to highlight the learning goals at the beginning of the experiment, prior to the example calculation, to help students relate the theoretical and practical aspects of buffer systems.

We have also incorporated organized questions at the end of the experiment to assess students' understanding of the core concepts and learning goals outlined in this lesson study. Students will explain how buffer strength and how resistance to pH is connected to concentration and also explore what components are needed to prepare a buffer.

Appendix A

Preparing and Using pH Buffered Solutions

Procedures:

Making a buffer of desired pH:

1. Choose a weak acid that has a pK_a near the pH of your buffer. Your buffer system should consist of that acid and its conjugate base.
2. Use the ICE table and K_a expression, or the Henderson-Hasselbalch equation, to calculate the concentration of the conjugate base needed to achieve your target pH.
3. Calculate the volume of the stock solution of the acid, which is needed to be used and diluted to the final volume (100.0 mL) in order to have 0.0500 M of the weak acid in the buffer.
4. Determine the number of moles and the mass of the conjugate base you need to add to achieve the desired concentration.
5. Measure and transfer the weak acid in a 100 mL volumetric flask. Dissolve the conjugate base solid in DI water and transfer it quantitatively to the flask. Swirl to dissolve all the solid particles completely.
6. Dilute it to the mark on the neck of the volumetric flask using DI water. Stopper it, invert, and mix it thoroughly.
7. Transfer the concentrated or high capacity buffer (HCB) into a 150 mL beaker and label it as HCB.

Investigating the buffer capacity:

1. Measure 20 ml of HCB and dilute it to 100.0 ml (use 25 ml graduated cylinder and volumetric flask) in order to prepare a low concentration buffer or low capacity buffer (LCB). Transfer the buffer into another 150 ml beaker and label it as LCB.
2. Use a 25 ml graduated cylinder to transfer 20 ml of HCB, LCB, and DI water into three small beakers. Calibrate your pH meter and measure the pH of each of the three solutions and record them.
3. Add 10 ml of HCl (use your 10 ml graduated cylinder) to each, mix and record the pH again.
4. Discard the solutions, rinse the beakers and dry them.
5. Again transfer 20 ml of HCB, LCB, and DI water into the small beakers.
6. Add 10 ml of NaOH to each beaker, measure the pH and record it.
7. Write your observation and ΔpH in each case.
8. Calculate the pH of each solution theoretically (homework).

Example:

Calculate the pH of a solution that is 0.200 M in NH_3 and 0.300 M in NH_4Cl.

K_a for $NH_4^+ = 5.68 \times 10^{-10}$

The equilibrium of interest is:

$NH_4^+ + H_2O \rightleftharpoons NH_3 + H_3O^+$

Calculate the pH of the buffer:

a) when 100.0 mL of 0.0500 M NaOH is added to 400 mL of the buffer solution.

b) when 100.0 mL of 0.0500 M HCl is added to 400 mL of the buffer solution..

CHM 104 Experiment 6 **Acids & Bases II: Preparing and Using a pH Buffered Solution**

Names:____ **Lab Section:** ___________

A. Preparation of Buffer Solutions

1. BUFFER TARGET pH: _____________

Data	Values
K_a of TRIS-acid	8.70×10^{-9}
Concentration of TRIS-acid Stock Solution	0.200 M
Molarity of TRIS-acid in Concentrated Buffer	0.0500 M
Molar Mass of TRIS-base ($C_4H_{11}NO_3$)	121.14 g/mol
Volume of Buffer Solution	100.0 mL

A. Show your calculation for the volume of Tris-A needed:

pK_a of Tris-Acid ___________

B. Show your calculations for the mass of Tris-B solid needed:

[Tris-B] in buffer ______________

Mass of Tris-B calculated ___________

Mass of Tris-B solid used ___________

2. <u>Dilute</u> Buffer: Prepare 100.0 mL of low-capacity buffer using high-capacity buffer.

Volume of HCB used = _________

Calculate the concentrations of Tris-A and Tris-B in diluted buffer (LCB). Show your work below.

$[\text{Tris-A}]_{diluted}$ _______________

$[\text{Tris-B}]_{diluted}$ _____________

DATA TABLE

Concentration of HCl ____________ Concentration of NaOH ___________

	Concentrated buffer (20.0 mL)	Diluted buffer (20.0 mL)	DI water (20.0 mL)
Measured pH of solution			
Measured pH after addition of 10.0 mL HCl			
Measured pH after addition of 10.0 mL NaOH			

Calculated pH of solution			
Calculated pH after addition of 10.0 mL HCl			
Calculated pH after addition of 10.0 mL NaOH			

Show ALL calculations on the following pages.

B. Calculated the pH of the prepared buffer solutions.

1. Write the chemical equilibrium for this buffer. Calculate the pH of the concentrated (high capacity buffer).

[Tris-A] = _________ [Tris-B] =____________

2. Write the chemical equilibrium for this buffer. Calculate the pH of the dilute (low capacity buffer).

$[\text{Tris-A}]_{\text{diluted}}$ = _________ $[\text{Tris-B}]_{\text{diluted}}$ =____________

3. Write the chemical equilibrium for auto-ionization of water and calculate the pH.

C. Calculated pH After Addition of HCl

1. Calculate the pH of 20.0 mL of the concentrated buffer (HCB) after the addition of 10.0 mL HCl.

Fill in the table below (Use moles for this table.)

HCl Neutralization Reaction	Tris-B + H_3O^+ $\longrightarrow$ Tris-A + H_2O
Before Reaction	
Change	
After Reaction	

[Tris-A] = ________ [Tris-B] = ________

Write the chemical equilibrium and calculate the pH:

2. Calculate the pH of 20.0 mL of the dilute buffer (LCB) after the addition of 10.0 mL HCl.

Fill in the table below (Use moles for this table.)

HCl Neutralization Reaction	Tris-B + H_3O^+ $\longrightarrow$ Tris-A + H_2O
Before Reaction	
Change	
After Reaction	

[Tris-A] = ________ [Tris-B] = ________

Calculate the pH:

3. Calculate the pH of 20.0 mL of water after the addition of 10.0 mL HCl.

D. Calculated pH After Addition of NaOH

1. Calculate the pH of 20.0 mL of the concentrated buffer (HCB) after the addition of 10.0 mL NaOH.

Fill in the table below (Use moles for this table.)

NaOH Neutralization Reaction	Tris-A + OH^- ⟶ Tris-B + H_2O
Before Reaction	
Change	
After Reaction	

[Tris-A] = ________ [Tris-B] = ________

Write the chemical equilibrium and calculate the pH:

2. Calculate the pH of 20.0 mL of the dilute buffer (LCB) after the addition of 10.0 mL NaOH.

Fill in the table below (Use moles for this table.)

NaOH Neutralization Reaction	Tris-A + OH^- ⟶ Tris-B + H_2O
Before Reaction	
Change	
After Reaction	

[Tris-A] = ________ [Tris-B] = ________

Calculate the pH:

3. Calculate the pH of 20.0 mL of water after the addition of 10.0 mL NaOH.

E. Answer the following question.

1. **How do the calculated pH values of the concentrated and dilute buffers compare? <u>Explain</u> what you observe.**

2. **Calculate the change in pH when HCl (ΔpH) was added to the concentrated (HCB) and diluted (LCB) buffers. Which buffer resists the change in pH more? Why (consider your BCA table)?**

3. **Calculate the change in pH when NaOH (ΔpH) was added to the concentrated (HCB) and diluted (LCB) buffers. Which buffer resists the change more? Why (consider your BCA table)?**

4. **Why does the pH of water change so dramatically when NaOH and HCl are added?**

5. **Describe (at least) 2 sources of experimental error that could contribute to differences between the measured and calculated pH of your buffer solutions.**

Appendix B

Pre-lab Quiz - Buffer Solutions

1) A Buffer Solution is defined as:

i) A mixture of a strong acid and its conjugate base, or vice versa, which resists changing its pH upon the addition of a weak base or a weak acid to it.
ii) A mixture of a weak acid and a strong base or vice versa which resists changing its pH upon the addition of a strong base or a strong acid to it.
iii) A mixture of a weak acid with its conjugate base, or vice versa, which resists changing its pH upon the addition of a strong acid or a strong base to it.
iv) A mixture of two salts which resists changing its pH upon the addition of any acid or base to it.

2) Which mixture of a weak acid and its conjugate base should be chosen in order to prepare a buffer with a pH=4.9?

i) Ammonia ($K_b = 1.80 \times 10^{-5}$) & Ammonium chloride ($K_a = 5.55 \times 10^{-10}$)
ii) Acetic acid ($K_a = 1.85 \times 10^{-5}$) & Sodium acetate ($K_b = 5.40 \times 10^{-10}$)
iii) Tris-acid ($Ka = 8.70 \times 10^{-9}$) & Tris-base ($K_b = 1.15\times 10^{-6}$)
iv) None of the above

3) Which of the following buffer solutions resists the change in pH more?

i) A buffer solution of 0.010 M acetic acid and 0.010 M sodium acetate
ii) A buffer solution of 0.10 M acetic acid and 0.10 M sodium acetate
iii) A buffer solution of 0.10 M acetic acid and 0.010 M of sodium acetate
iv) A buffer solution of 0.010 M acetic acid and 0.10 M sodium acetate

4) What is the pH of a buffered solution that is 0.043 M in Tris-acid and 0.050 M in Tris-base? (PKa of Tris-acid = 8.06)

i) 7.56å
ii) 8.13
iii) 4.7
iv) 8.06