Buffers in Household Products

Introduction

One of the most important applications of acids and bases in chemistry and biology is that of buffers. A buffer solution resists rapid changes in pH when acids and bases are added to it. Many consumer products are buffered to maintain and safeguard their activity. How do we discover which products have buffering capacity?

Concepts

- Buffer
- Conjugate acid–base pair
- Neutralization
- Weak acids and weak bases
- Dissociation constant
- Titration

Background

Many chemical reactions in living organisms take place at neutral pH values. Even a small change in pH can cause some of nature's catalysts (the enzymes) to stop functioning. The pH level in blood, for example, must be maintained within extremely narrow limits.

The ability of buffers to resist changes in pH upon addition of acid or base can be traced to their chemical composition. All buffers contain a mixture of either a weak acid (HA) and its conjugate base (A^-), or a weak base and its conjugate acid. The buffer components HA and A^- are related to each other by means of the following chemical reaction that describes the behavior of a weak acid in water (Equation 1).

$$\underset{\text{weak acid}}{HA} + H_2O \rightleftarrows \underset{\text{conjugate base}}{A^-} + H_3O^+ \qquad \textit{Equation 1}$$

Buffers control pH because the two buffer components are able to react with and therefore neutralize the strong acid or strong base that might be added to the solution. The weak acid component HA reacts with any strong base, such as sodium hydroxide (NaOH), to give water and the conjugate base component A^- (Equation 2). The conjugate base component A^- reacts with any strong acid, such as hydrochloric acid (HCl), to give its acid partner HA and a chloride ion (Equation 3).

$$HA + NaOH \rightleftarrows Na^+ + A^- + H_2O \qquad \textit{Equation 2}$$

$$A^- + HCl \rightleftarrows HA + Cl^- \qquad \textit{Equation 3}$$

These neutralization reactions can be visualized as a cyclic process (Figure 1). Buffer activity will continue as long as both components are present in solution. Once either component is consumed, the buffer capacity will be exhausted and the buffer will no longer be effective.

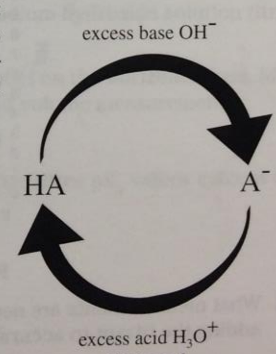


Figure 1.

A buffer composed of an equal number of moles of a weak acid and its conjugate base is generally equally effective in resisting pH changes upon addition of either acid or base. The pH range in which a buffer system will be effective is called its *buffer range*. The buffer range is usually limited to 2 pH units centered around the pH of the equimolar or ideal buffer solution. An ideal carbonic acid–bicarbonate buffer, for example, has a pH of 6.4 and its buffer range is pH 5.4–7.4.

For buffers to be effective, noticeable amounts of both the weak acid and its conjugate base pair must be present. This limits the concentration ratios for $HA:A^-$ or $B:BH^+$ to between 10:1 and 1:10 and the pH range for the buffering action of any weak acid to $pK_a \pm 1$.

Buffers are also important in certain commercial household products. Soaps and shampoos are, by nature, alkaline. The addition of citric acid buffers this alkalinity and prevents possible burns to the skin and scalp. Baby lotions often contain citric acid and sodium lactate to buffer the lotion to a slightly acidic pH of six, which inhibits the growth of bacteria and other pathogens. Even alcohol production can rely on buffers. Yeasts that ferment the sugars only work within a narrow pH range. If the pH is outside the range of 4.0–6.0, yeast growth may be inhibited or even destroyed.

Experiment Overview

The purpose of this advanced inquiry lab is to investigate the buffering capacity and buffer components of various consumer products. Many household products contain buffering chemicals such as citric acid, sodium carbonate, sodium benzoate, and phosphates or phosphoric acid. The lab begins with an introductory activity—generating the titration curve for citric acid—to identify the buffering regions in the neutralization of a polyprotic weak acid. The results provide a model for guided-inquiry design of a procedure to determine the buffering agents in eight different household products, including foods and beverages and over-the-counter drugs. Procedures may include creating titration curves, calculating pK_a values, and analyzing the buffer capacity and composition. Students may recommend additional consumer products for further inquiry.

Pre-Lab Questions

Figure 2 shows the pH curve for the titration of 25.0 mL of a 0.10 M solution of acetic acid, CH_3COOH, with 0.10 M sodium hydroxide solution. K_a of acetic acid is 1.8×10^{-5}.

1. At what point in the titration does the concentration of acetic acid, CH_3COOH, equal the concentration of the acetate ion, CH_3COO^-? What is the pH of the equimolar, ideal buffer solution at this point?
2. If this weak acid is effective as a buffer between the concentration ratios for the conjugate acid–base pair of 10:1 and 1:10, what pH range does this cover?

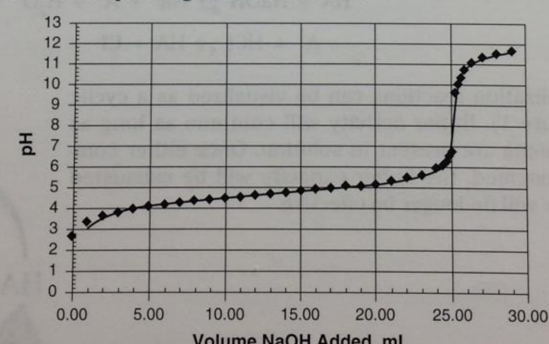


Figure 2. Titration of Acetic Acid with NaOH

3. What measurements are needed in the titration of a weak acid? Explain in detail the technique for adding the titrant to accurately determine the concentration and pK_a of the weak acid.

Materials (for each lab group)

Citric acid solution, $C_6H_8O_7$, 0.02 M, 20 mL*	Buret, 50-mL
Hydrochloric acid solution, HCl, 0.1 M, 150 mL	Clamp, buret
Sodium hydroxide solution, NaOH, 0.1 M, 150 mL	Magnetic stirrer and stir bar
Water, distilled or deionized	pH meter or pH sensor
Beakers, 150-mL, 2	Support stand
Beakers, 250-mL, 2	Wash bottle

**The concentration is approximately 0.02 M.*

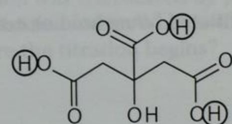
Safety Precautions

All the acids and bases used in this lab are irritating to eyes, skin, and other body tissues. Avoid contact of all chemicals with eyes and skin. Wear chemical splash goggles, chemical-resistant gloves, and a chemical-resistant apron. Wash hands thoroughly with soap and water before leaving the lab. Please follow all laboratory safety guidelines.

Introductory Activity

Titration of Citric Acid

Citric acid (H_3A) is a common buffer added to consumer products. This weak acid contains three ionizable hydrogen atoms.



The ionizable hydrogen atoms create three possible buffer regions:

Region 1: $H_3A + H_2O \rightleftarrows H_2A^- + H_3O^+$ $K_{a1} = 8.4 \times 10^{-4}$

Region 2: $H_2A^- + H_2O \rightleftarrows HA^{2-} + H_3O^+$ $K_{a2} = 1.8 \times 10^{-5}$

Region 3: $HA^{2-} + H_2O \rightleftarrows A^{3-} + H_3O^+$ $K_{a3} = 4.0 \times 10^{-6}$

1. Set up a pH meter and electrode. Calibrate the pH meter.
2. Fill the buret with the 0.1 M sodium hydroxide, NaOH, solution.
3. Titrate 20 mL of the citric acid solution, $C_6H_8O_7$, with the sodium hydroxide solution titrant. Record your data.
4. Graph the data, with pH on the vertical axis and volume NaOH on the horizontal axis. Make the graph large enough to reflect the care taken with the pH and volume measurements.

Analyze the Results

What is the buffering region of the citric acid titration curve? Are three pK_a values evident in the results? Explain.

Guided-Inquiry Design and Procedure

Form a working group with other students and select two consumer products for testing. Discuss the following questions as you design a procedure for analyzing the potential buffer capacity of the products.

1. What is the form of the sample product? Can it be made into a solution for testing?
2. Is the product acidic or basic? What is the appropriate titrant for analyzing the product?
3. What is a suitable concentration of the sample solution to be analyzed? Should it be diluted or concentrated?
4. How can you determine the proper amount of sample solution for testing?
5. What data must be collected and how should the data be graphed or evaluated?
6. Write a detailed, step-by-step procedure for investigating the buffer capacity and identifying the buffer components in an unknown consumer product. Include the materials and equipment that will be needed, safety precautions that must be followed, amounts of chemicals to use, etc.
7. Carry out the procedure on the selected products and record results in appropriate data tables.

Analyze the Results

Does the product contain a buffer? If so, what is the buffering range? Estimate the pK_a value(s) for the buffer and identify the potential buffering components in the product.

Opportunities for Inquiry

Students may recommend additional household or consumer products for analysis.

AP Chemistry Review Questions

Integrating Content, Inquiry and Reasoning

1. Fill in the chart below with the formula of the missing conjugate acid or base.

Conjugate Acid	Conjugate Base
$HC_2H_3O_2$	
	CN^-
HSO_4^-	
	CO_3^{2-}

2. A buffer is prepared using the conjugate acid–base pair acetic acid and acetate ions. Write chemical equations showing the reactions that take place when H^+ and when OH^- are added to the buffer.

The approximate concentration of a hydrochloric acid solution is 0.5 M. The exact concentration of this solution is to be determined by titration with 0.215 M sodium hydroxide solution.

3. A 10.00-mL sample of the HCl solution was transferred by pipet to an Erlenmeyer flask and then diluted by adding about 40 mL of distilled water. What is the approximate H_3O^+ concentration and pH of the solution in the flask before the titration begins?

4. Phenolphthalein indicator was added, and the solution in the flask was titrated with 0.215 M NaOH until the indicator just turned pink (pH = 8–9). The exact volume of NaOH required was 22.75 mL. Calculate the concentration of HCl in the original 10.00-mL sample.

5. One student accidentally "overshot" the endpoint and added 23.90 mL of 0.215 M NaOH. Is the calculated concentration of HCl likely to be too high or too low as a result of this error?