BUFFERS IN HOUSEHOLD PRODUCTS
AP* Chemistry Big Idea 6, Investigation 15
An Advanced Inquiry Lab

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. Every living cell contains natural buffer systems to maintain the constant pH needed for proper cell function. Many consumer products are buffered to maintain and safeguard their activity. How do we discover which products have buffering capacity?

Concepts

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

Equation 1

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

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).

Equation 2

$$HA + NaOH \rightleftarrows Na^+ + A^- + H_2O$$

Equation 3

$$A^- + HCl \rightleftarrows HA + Cl^-$$

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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.

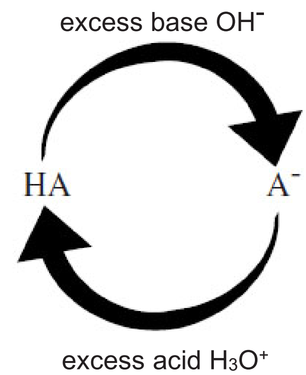

Figure 1.

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.

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Prelab 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?

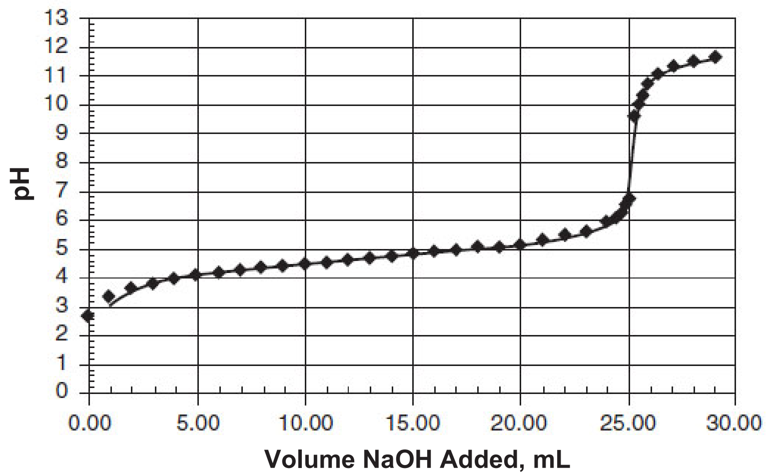

Figure 2. Titration of Acetic Acid with NaOH

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

Materials

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

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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.

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Teacher's Notes

Investigation 15—Buffers in Household Products

Part I. Lab Preparation

Materials Included in Kit (for 24 students working in pairs)

Citric acid, $C_6H_8O_7$, 3 g

Hydrochloric acid solution, HCl, 0.1 M, 2.0 L

Sodium hydroxide solution, NaOH, 0.1 M, 2.0 L

Alka-Seltzer® tablets, 6

Gatorade®, G2 series, red, 12-ounce bottle

Lemon-lime Kool-Aid® packets, 3

Lactaid® tablets, 4

Pineapple juice, 6-ounce cans, 2

Starch, liquid, 50 mL

Tomato paste, 6-ounce can

Tonic water, 1-liter bottle

Additional Materials Required (for each lab group)

Water, distilled or deionized

Water, distilled or deionized

Beakers, 150-mL, 2

Beakers, 250-mL, 2

Buffer, pH 7 (to calibrate pH meter)

Buret, 50-mL

pH sensor or pH meter

Clamp, buret

Magnetic stirrer and stir bar

pH sensor or pH meter

Support stand

Wash bottle

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Additional Materials Required (for Prelab Preparation)

Balance, 0.01-g precision

Volumetric flask, 500-mL

Time Required

This laboratory activity can be completed in two 50-minute class periods. It is important to allow time between the *Introductory Activity* and the *Guided-Inquiry Activity* for students to discuss and design the guided-inquiry procedures. Also, all student-designed procedures must be approved for safety before students are allowed to implement them in the lab. *Prelab Questions* may be completed before lab begins the first day.

Prelab Preparation

To prepare 500 mL of 0.02 M citric acid solution:

1. Fill a 500-mL volumetric flask about one-half full with distilled or deionized water.
2. Mass 2.10 g of the citric acid on the balance. Add the solid to the 500-mL volumetric flask and shake to dissolve.
3. Fill the flask to the mark with distilled or deionized water. Mix well before dispensing.

Safety Precautions

All the acids and bases used in this lab are irritating to eyes, skin, and other body tissues. Wear chemical splash goggles, chemical-resistant gloves, and a chemical-resistant apron. Remind students to wash their hands thoroughly with soap and water before leaving the lab. Please review current Safety Data Sheets for additional safety, handling, and disposal information.

Disposal

Please consult your current *Flinn Scientific Catalog/Reference Manual* for general guidelines and specific procedures, and review all federal, state and local regulations that may apply, before proceeding. The citric acid and hydrochloric acid solutions may be neutralized according to Flinn Suggested Methods #24a and #24b, respectively. The sodium hydroxide solutions may be neutralized according to Flinn Suggested Disposal Method #10. The titrated solutions and leftover liquid products may be rinsed down the drain with excess water according to Flinn Suggested Disposal Method #26b.

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Part II. Teacher Guidance

Alignment to AP Chemistry Curriculum Framework

Enduring Understandings and Essential Knowledge

Chemical changes are represented by a balanced chemical equation that identifies the ratios with which reactants react and products form. (3A)

3A2: Quantitative information can be derived from stoichiometric calculations that utilize the mole ratios from the balanced chemical equations. The role of stoichiometry in real-world applications is important to note, so that it does not seem to simply be an exercise done only by chemists.

Chemical reactions can be classified by considering what the reactants are, what the products are, or how they change from one into the other. Classes of chemical reactions include synthesis, decomposition, acid−base, and oxidation−reduction reactions. (3B)

3B2: In a neutralization reaction, protons are transferred from an acid to a base.

Chemical equilibrium plays an important role in acid–base chemistry and in solubility. (6C)

6C1: Chemical equilibrium reasoning can be used to describe the proton transfer reactions of acid–base chemistry.

6C2: The pH is an important characteristic of aqueous solutions that can be controlled with buffers. Comparing pH to pK_a allows one to determine the protonation state of a molecule with a labile proton.

Learning Objectives

3.4 The student is able to relate quantities (measured mass of substances, volumes of solutions, or volumes and pressures of gases to identify stoichiometric relationships for a reaction, including situations involving limiting reactants and situations in which the reaction has not gone to completion.

3.7 The student is able to identify compounds as Brønsted-Lowry acids, bases, and/or conjugate acid−base pairs, using proton-transfer reactions to justify the identification.

6.12 The student can reason about the distinction between strong and weak acids solutions with similar values of pH, including the percent ionization of acids, the concentrations needed to achieve the same pH, and the amount of base needed to reach the equivalence point in a titration.

6.16 The student can identify a given solution as being the solution of a monoprotic weak acid or base, including salts in which one ion is a weak acid or base), calculate the pH and concentration of all species in solution, and/or infer the relative strengths of the weak acids or bases from given equilibrium concentrations.

6.19 The student can relate the predominant form of a chemical species involving a labile proton (i.e., protonated/deprotonated form of a weak acid) to the pH of a solution and the pK_a associated with the labile proton.

6.20 The student can identify a solution as being a buffer solution and explain the buffer mechanism in terms of the reactions that would occur on addition of acid or base.

Science Practices

2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

2.3 The student can estimate numerically quantities that describe natural phenomena.

4.2 The student can design a plan for collecting data to answer a particular scientific question.

5.1 The student can analyze data to identify patterns or relationships.

6.1 The student can justify claims with evidence.

6.4 The student can make claims or predictions about natural phenomena based on scientific theories and models.

7.2 The student can connect concepts in and across domains to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

Lab Hints

- Citric acid has overlapping buffer regions that prevent a rapid rise in pH between ionizable protons, as with many other polyprotic weak acids, such as phosphoric acid.
- Students may need to consider the molar mass of possible buffer components when determining sample size. Have them assume a 100 g/mole molar mass for the component.
- Equilibrium constants and pK_a values are temperature dependent. The pH of an ideal buffer will change by up to 0.1 pH unit per degree Celsius.

Part III. Sample Data, Results, and Analysis

Answers to Prelab Questions (Student answers will vary.)

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?

   These two are equal at half titration of 12.5 mL of NaOH. At this point pH = pK_a = 4.74.

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?

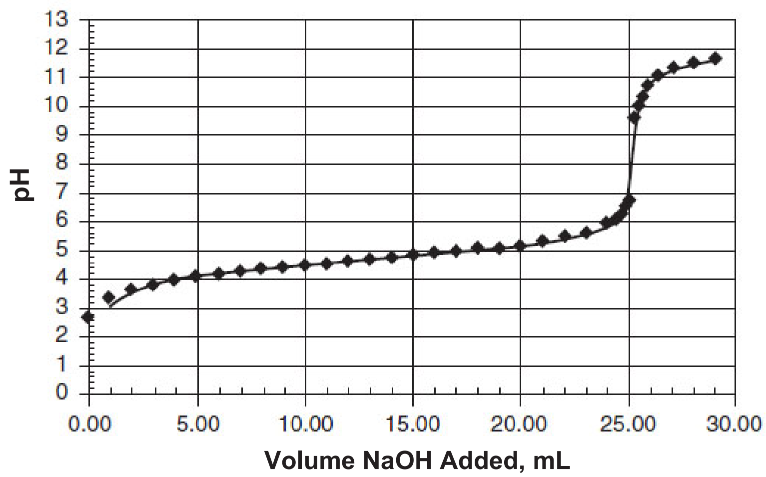

Figure 2. Titration of Acetic Acid with NaOH

   At the conjugate acid–base pair of 10:1

   $pH = pK_a + \log([A^-]/[HA]) = 4.74 + \log(1/10) = 3.74$

   At the conjugate acid–base pair of 1:10

   $pH = pK_a + \log([A^-]/[HA]) = 4.74 + \log(10/1) = 5.74$

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

   Titrations are carried out by measuring the pH of a solution as a function of the volume of titrant (mL) added. To ensure accuracy, the titrant must be added in small volume increments, no more than 1 mL at a time, and preferably dropwise in the region of the equivalence point. The desired precision in volume measurements is achieved using a buret.

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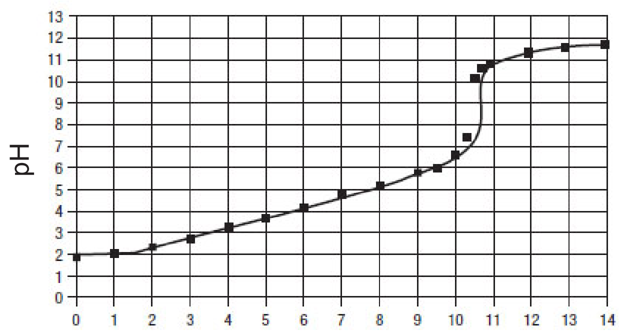
Sample Data for Introductory Activity



Analyze the Results

Citric acid solutions form effective buffers in the pH range from 2.5 to 6.0. Individual pK_a values cannot be distinguished in the titration curve for the stepwise dissociation of the triprotic acid.

Answers to Guided-Inquiry Discussion Questions

1. What is the form of the sample product? Can it be made into a solution for testing?

The samples that are provided may be in either solid (Alka-Seltzer, Lactaid, Kool-Aid) or liquid form (Gatorade, pineapple juice, starch, tomato paste, tonic water). The paste or solids may be mixed with water to form solutions.

2. Is the product acidic or basic? What is the appropriate titrant for analyzing the product?

The samples (or sample solutions) should be tested with a pH meter before titrating them. Samples that are acidic (pH <7) should be titrated with 0.1 M NaOH solution. Basic samples (pH >7) should be titrated with 0.1 M HCl solution. Neutral substances such as Alka-Seltzer may be titrated with both acid and base.

3. What is a suitable concentration of the sample solution to be analyzed? Should it be diluted or concentrated?

Concentrations must be adjusted for convenient titration, so that the amount of titrant needed is neither too large (>25 mL) nor too small (<5 mL). This can be determined by doing a rough titration.

4. How can you determine the proper amount of sample solution for testing?

Carry out a rough titration of each sample (20 mL) by adding acid or base 1–2 mL at a time.

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5. What data must be collected and how should the data be graphed or evaluated?

Titration curves are generated by plotting pH versus volume (mL) of acid or base added. The titration curves should be analyzed to see if they have relatively flat regions where the pH does not change much as acid or base is added. These are the buffering regions. The pH value in a buffering region reflects the pK_a of the weak acid or base.

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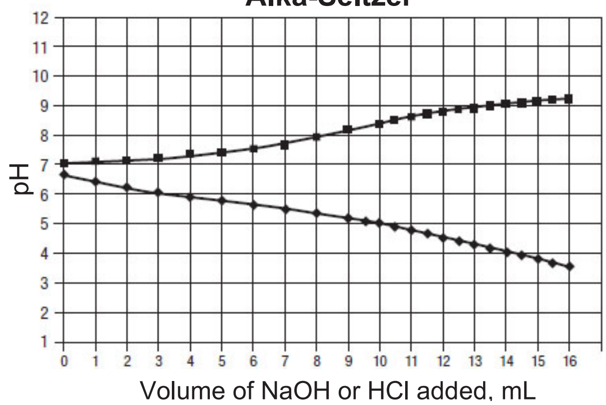
Sample Data and Graphs for Guided-Inquiry Activity

Alka-Seltzer®



Alka-Seltzer® tablets contain two buffering compounds, citric acid and sodium bicarbonate.

Citric acid dissolves to give it conjugate base form $C_6H_7O_7^-$.

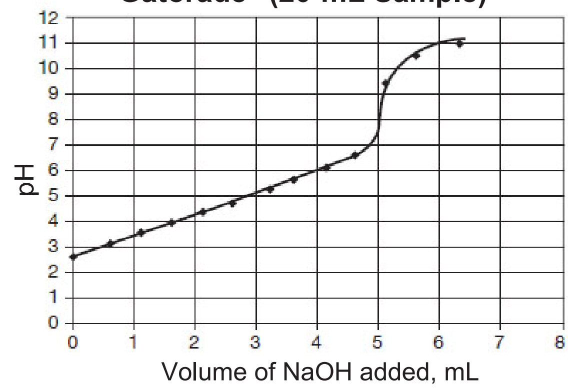
The citric acid buffers when base is added:

$C_6H_8O_7 + OH^- \rightarrow C_6H_7O_7^- + H_2O$

While the bicarbonate buffers when acid is added:

$HCO_3^- + H_3O^+ \rightarrow H_2CO_3 + H_2O$

Gatorade® (20-mL Sample)



Gatorade® drink contains two buffering compounds: citric acid and potassium phosphate monobasic, KH_2PO_4.

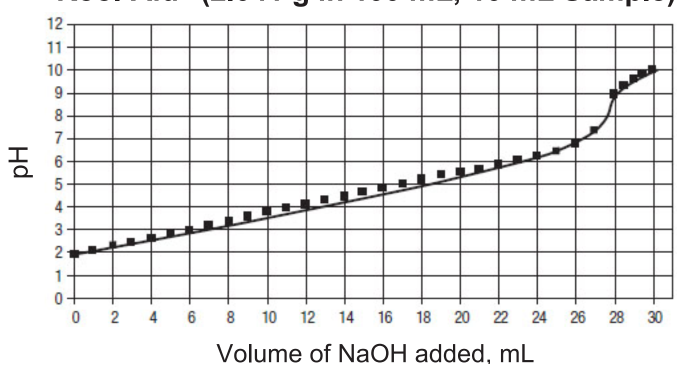
The citric acid buffers when base is added:

$C_6H_8O_7 + OH^- \rightarrow C_6H_7O_7^- + H_2O$

As does the dihydrogen phosphate ion:

$H_2PO_4^- + OH \rightarrow HPO_4^{2-} + H_2O$

Kool-Aid® (2.041 g in 100 mL, 10 mL Sample)



Kool-Aid® drink mixture contains two buffering compounds: citric acid and ascorbic acid.

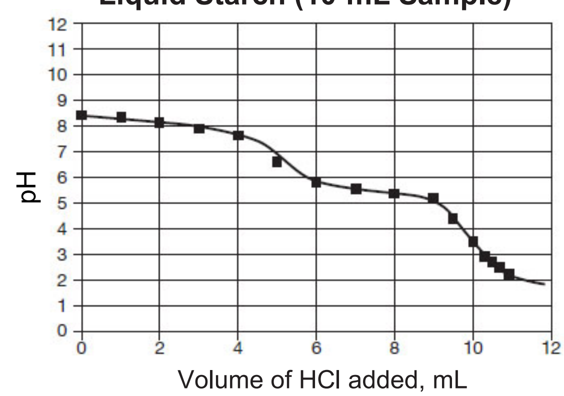
The citric acid buffers when base is added:

$C_6H_8O_7 + OH^- \rightarrow C_6H_7O_7^- + H_2O$

As does the ascorbic acid:

$C_6H_8O_6 + OH^- \rightarrow C_6H_7O_6^- + H_2O$

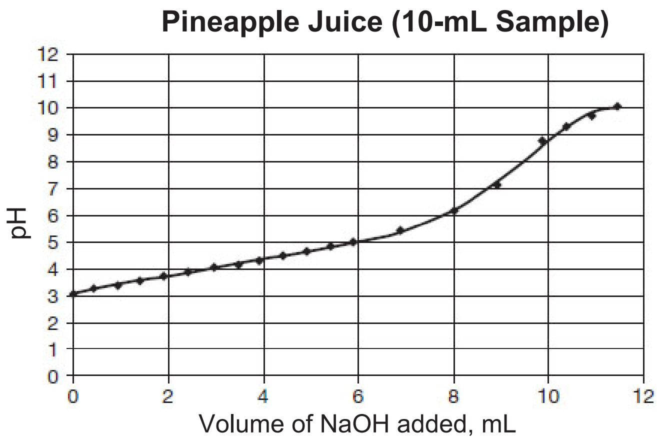
Liquid Starch (10-mL Sample)



The liquid starch contains one buffering compound: sodium tetraborate.

The tetraborate ion buffers when base is added:

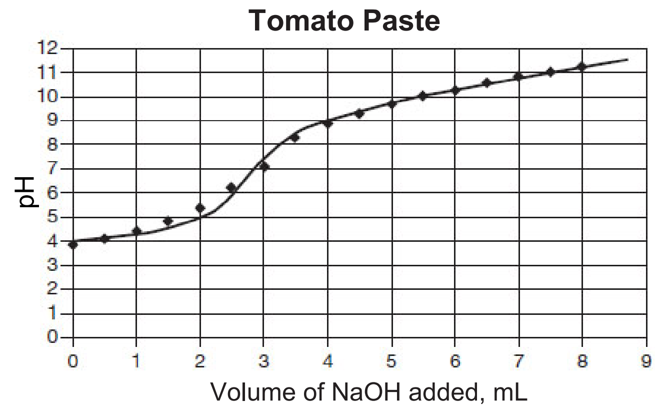
$B_4O_7^{2-} + H_3O^+ \rightarrow HB_4O_7^- + H_2O$



The pineapple juice contains one buffering compound: ascorbic acid.

The ascorbic acid buffers when base is added:

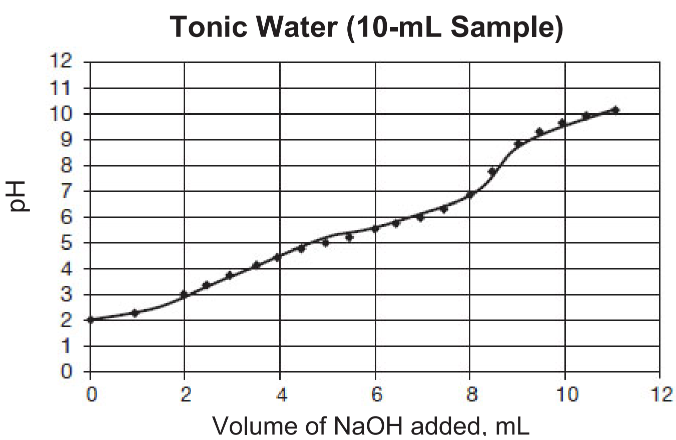
$C_6H_8O_6 + OH^- \rightarrow C_6H_7O_6^- + H_2O$



The tomato paste contains one buffering compound: ascorbic acid.

The ascorbic acid buffers when base is added:

$C_6H_8O_6 + OH^- \rightarrow C_6H_7O_6^- + H_2O$



Tonic water contains three buffering compounds: citric acid, sodium benzoate and quinine.

The citric acid buffers when base is added:

$C_6H_8O_7 + OH^- \rightarrow C_6H_7O_7^- + H_2O$

Sodium benzoate and quinine are bases and may buffer if acid is added.

The Lactaid® tablets contain no buffering compounds.

Reference

AP Chemistry Guided-Inquiry Experiments: Applying the Science Practices;* The College Board: New York, NY, 2013.

***Buffers in Household Products—Advanced Inquiry Laboratory Kit* and supporting materials are available from Flinn Scientific, Inc.**

Catalog No.	Description
AP7665	Buffers in Household Products— Advanced Inquiry Laboratory Kit
AP8673	pH Meter
B0117	Buffer Envelope, pH 7

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