Advanced Chemistry through Inquiry

Teacher Guide

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CONTRIBUTORS

Contributing POGIL Authors

- Rick Moog, *Director of The POGIL Project; Professor of Chemistry,* Franklin & Marshall College
- Laura Trout*, Editor-in-Chief for the High School POGIL Initiative; Science Department Chair,* Lancaster Country Day School, Lead Author
- Melissa Hemling, *Chemistry Instructor and Science Department Chair,* Beaver Dam High School
- Stephen Prilliman, *Associate Professor of Chemistry,* Oklahoma City University
- Amanda Zullo, *Associate Editor for the High School POGIL Initiative; Chemistry Instructor*, Saranac Lake High School
- Cameron Rekully, *Graduate Student*, University of South Carolina

PASCO Development Team

- Freda Husic, *Director of Education Solutions*, *Program Manager*
- Tom Loschiavo, *Chemistry Education Manager*
- Ronn Fieldhouse, *Chemistry Curriculum and Training Specialist*
- Janet Miller, *Lead Editor*
- Brennan Collins, *Graphics and Production*

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INTRODUCTION

PASCO scientific's *Advanced Chemistry through Inquiry* investigations move students from the low-level task of memorization or confirmation of science facts to higher-level tasks of exploration, data analysis, concept construction, and application. To learn science at a deep level, it is essential to combine the teaching of abstract science concepts with real-world science investigations. Hands-on technology-based laboratory experiences bridge the gap between the theoretical and the concrete, driving students toward a greater understanding of natural phenomena. Students also gain experience with important science practices that include: developing and using models, planning and carrying out independent investigations, interpreting data, and applying mathematics.

Each lab is divided into several *models*. A model is a set of data or symbolic representations that students build and use as they work through a set of questions designed to construct an understanding of chemical concepts. The models are sequential, with each model introducing a new aspect to the investigation. Guiding questions embedded in the procedure help generate insight into the chemical process and theory. As students follow the cognitive process to completion, they actively think about and work through chemistry-related problems. The entire approach, including the guiding questions and the models, is based on the POGIL™ (Process Oriented Guided Inquiry Learning) strategy.

What is POGIL?

POGIL uses guided inquiry – a learning cycle of exploration, concept invention, and application that is the basis for the carefully designed materials that assist students in constructing new knowledge. It is a student-centered strategy; students work in small groups with individual roles to ensure that all students are fully engaged in the learning process.

The lab activities focus on core concepts and encourage a deep understanding of the course material while developing higher-order thinking skills. POGIL develops process skills such as critical thinking, problem solving, and communication through cooperation and reflection, helping students to think analytically and work effectively as part of a collaborative team.

A POGIL lab consists of any number of students working in small groups on specially designed guided inquiry materials. These materials supply students with data or information followed by leading questions and experiments that guide them to their own valid conclusions—essentially a recapitulation of the scientific method. The instructor serves as facilitator, observing and periodically addressing individual and classroom-wide needs.

POGIL is based on research indicating that: a) *teaching by telling* does not work for most students, b) students who are part of an interactive community are more likely to be successful, and c) knowledge is personal; students enjoy themselves more and develop greater ownership over the material when they are given an opportunity to construct their own understanding.

A discovery-based team environment energizes students and provides instructors with instant and constant feedback about what their students understand *and misunderstand*. Students quickly pick up the message that logical thinking and teamwork are prized above simply getting "the correct answer." This emphasizes that learning is not a solitary task of memorizing information, but an interactive process of refining one's understanding and developing one's skills.

Teacher Resources and Student Handouts

All teacher and student materials are on the storage device accompanying the printed lab manual. Teacher Resources are in PDF format, but the Student Handouts are in Microsoft® Word format, allowing you to customize the labs for your curriculum, students, and equipment.

Teacher Resources. Each Teacher Resource file contains a lab activity. These files contain all the sections of the Student Handouts, such as the activity procedure and guiding questions (Building Model *n,* where *n* is the model number; there are at least two models built and analyzed in a lab activity), the data that describe the model (Model *n*), and the analysis questions (Analyzing Model *n*), as well as the teacher-specific sections including time requirements, alignment to the AP® Chemistry learning objectives and science practices, lab preparation, and teacher tips to help ensure success. Sample data is provided for the investigations and sample answers are provided for all questions.

Student Handouts. The handout begins with a brief question to focus the investigation, followed by a series of questions that relate to the models. For their investigations, students build two to three models and analyze each one. Finally, students make connections to theory and apply their knowledge to design and carry out their own extended investigation.

Lab Activity Components

The sections in each teacher and student activity

TEACHER RESOURCES	STUDENT HANDOUT
Initial Question	Initial Question
Learning Objectives	
Time Requirements	
Materials and Equipment	Materials and Equipment
Prerequisites	
Lab Preparation	
Safety	Safety
Getting Your Brain in Gear	Getting Your Brain in Gear
Building Model 1*	Building Model 1*
Model 1*	Model 1*
Analyzing Model 1*	Analyzing Model 1*
Connecting to Theory	Connecting to Theory
Applying Your Knowledge	Applying Your Knowledge

*All labs have at least two Models that go through the "Build, Model, Analyze" cycle.

Overview of Lab Activity Components

INITIAL QUESTION

Each activity starts with a question that drives the overall investigation.

LEARNING OBJECTIVES (TEACHER RESOURCES ONLY)

Each lab activity is aligned to the Learning Objectives and Scientific Practices from the College Board's *AP Chemistry Course and Exam Description*, Effective Fall 2013 (revised edition).

TIME REQUIREMENT (TEACHER RESOURCES ONLY)

This section provides two pieces of information: preparation time and the length of the lab activity. The time estimate includes the time required to complete the models and model analysis, and for students to plan and carry out their investigations.

MATERIALS AND EQUIPMENT

This section lists all materials and equipment needed to carry out the investigations for each of the models and for the students' extended investigation. If items in this list need to be created using

additional materials, those are indicated as a footnote in the Teacher Resources version, and instructions for preparing them are in the Lab Preparation and Teacher Tips sections.

LAB PREPARATION (TEACHER RESOURCES ONLY)

Although pre-made chemicals can be purchased to conduct these activities, this section provides instructions for making the solutions from concentrated or stock solutions, and for assembling any material that requires special preparation.

SAFETY

This section lists the pertinent safety procedures for the lab.

GETTING YOUR BRAIN IN GEAR

In place of a traditional Pre-Lab activity, the "Getting Your Brain in Gear" section is a set of questions that form the framework of concepts that will be developed in the investigation.

BUILDING MODEL N (WHERE N IS THE MODEL NUMBER; THERE ARE AT LEAST TWO MODELS BUILT AND ANALYZED IN A LAB ACTIVITY)

This is the procedure, with embedded guiding questions, for one section of data collection in the lab. In many cases, student groups carry out similar reactions with different compounds, or for different lengths of time, and then share their data so they can observe a greater scope of results.

MODEL N

This section contains the data or symbolic representation obtained while building the model. The data may be organized in various formats, including graphs and tables. This information is the basis for the analysis section.

ANALYZING MODEL N

This section contains guided inquiry analysis questions that lead students through exploration and concept invention based on the model.

CONNECTING TO THEORY

This section is a more refined description of the theory that the students constructed from the concepts developed throughout the learning cycle activities in the investigation.

APPLYING YOUR KNOWLEDGE

Students are given a question or activity for which they must apply the science skills and concepts developed throughout the investigation in a new or unique context.

The Data Collection System

In this manual, *data collection system* refers to the system employed by students to record, visualize, and analyze sensor data during their experiments. The system consists of all components necessary to connect a sensor to a device containing the software that detects the sensor measurement and collects, records, and displays this data.

Some systems, such as the Xplorer GLX® or SPARK Science Learning System™, are stand-alone systems. These contain built-in software applications, and students simply attach a sensor and begin collecting data. Other systems use a computer or tablet with downloaded software applications. In these systems, a USB or Bluetooth® interface is used to connect a sensor to the device. Software options for these include SPARKvue® version 2 and PASCO Capstone™ software.

The activities are designed so that any PASCO data collection system can be used to carry out the procedures.

Getting Started with Your Data Collection System

To help you and your students become familiar with the many features of your data collection system, start with the tutorials and instructional videos available in the video library on PASCO's website (www.pasco.com). Each system's software also has a built-in help system.

Free SPARKlab™ activities are included in the SPARKvue software. Performing one of these activities can be a good starting place for students to become familiar with connecting a sensor, viewing data, saving their work, and other tasks related to probeware use.

The technical and teacher support team at PASCO scientific provides timely and comprehensive help to teachers and students using PASCO products.

1-800-772-8700 / email: support@pasco.com / www.pasco.com/support

Electronic Materials

A USB storage device was included with the purchase of this manual and is attached to its inside cover. Please view the "contents.pdf" file for a list of the included resources.

Using *ODYSSEY* Molecular Labs

The Advanced Chemistry Through Inquiry guide comes with *ODYSSEY* Molecular Labs. Wavefunction's ODYSSEY is a unique software program for use in chemistry classes. Maker of *Spartan* molecular modeling software, Wavefunction created *ODYSSEY* so students could use scientifically-based simulations to experiment with core chemistry topics from a molecular perspective. The additional perspective provided by the *ODYSSEY* software enhances and complements the hands-on, experimental PASCO activities in this manual.

College Board* Advanced Placement (AP*) Program

The College Board developed a framework for the AP Chemistry curriculum centered on 6 Big Ideas. To develop conceptual understanding of the Big Ideas, students combine specific learning objectives with reasoning skills and science practices.

While this lab manual was not developed by the College Board, the activities are aligned to specific learning objectives and science practices from the AP Chemistry Curriculum Framework, from in the *AP Chemistry Course and Exam Description*.

NOTE: In the table showing the Learning Objectives and Science Practices that apply to an activity, the primary learning objective for that activity is shown in a **bold** *type.*

International Baccalaureate Organization (IBO**) Support

The International Baccalaureate Organization (IBO) uses a specific science curriculum model that includes both theory and practical investigative work. While this lab guide was not produced by the IBO, the lab activities can be adapted easily to the IB classroom.

By the end of the IB Diploma Program students are expected to have completed a specified number of practical investigative hours and are assessed using the specified internal assessment criteria. Students should be able to design a lab based on an original idea, carry out the procedure, draw conclusions, and evaluate their results. These scientific processes require an understanding of laboratory techniques and equipment as well as a high level of thinking, skills that are developed and sharpened by completing the investigations in this manual.

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AP and IBO Correlations

AP and IBO correlations to the activities in this manual
*NOTE: The primary learning objective for that activity is shown in a **bold** type.*

Activity	Lab Activity	AP Learning Objective	AP Science Practice	IBO Standard
1	*Modeling Chemistry* Students compare various physical and chemical changes while gaining an understanding of sensors and representing reactions at the particulate level.	2.3, 2.5, 3.1, **3.10**, 5.10	1.1, 1.3, 1.4, 4.3, 5.1, 5.2, 6.1, 6.2, 6.4	4.5
2	*Light, Color, and Concentration* Students learn how to use visible light to determine the concentration of colored ion species in a solution.	**1.16**	4.1, 4.2, 4.3, 5.1, 5.3	1.5, A.8
3	*Gravimetric Analysis* Through gravimetric analysis, students identify an unknown alkali metal carbonate.	1.3, **1.19**	4.3, 5.2, 6.1	1.4
4	*Stoichiometry of Solutions* Students perform analytical techniques to determine the concentrations of dissolved ions.	1.20, 3.3, **3.4**	2.2, 5,1, 6,4	1.5
5	*Polar and Nonpolar Substances* Students understand how a compound's structure influences its solubility in water and oil. They apply this knowledge to extract polar and nonpolar compounds from a mixture.	**2.8**, 2.13	1.4, 5.1, 6.1, 6.2	4.3, 4.5
6	*Solubility* Students determine the saturation concentration of a compound and the mass of a dissolved solute.	2.15, 2.19, **6.21**	4.3	1.5
7	*Empirical Formula* Students use stoichiometric calculations to analyze the results of a reaction carried out in the laboratory.	**3.6**	2.2, 5.1	1.2
8	*Measuring Vitamin C – A Redox Titration* Students expand their understanding of titrations, carry out a redox titration, and then use the redox titration method to answer a question of their own design.	**3.9**, 1.20	4.2, 4.3, 5.1	9.1, 9.2
9	*Factors that Affect Reaction Rate* Students explore several variables that could affect the rate of a chemical reaction.	**4.1**	4.2, 5.1	6.1, A.8
10	*Measuring the Speed of a Reaction* Students determine the order of a reaction and the effect of variables on the reaction rate.	**4.2**	4.2, 5.1, 5.3	6.1, 16.1, 16.3
11	*Energy in Chemical Reactions* Students demonstrate that the heat q is dependent on reaction conditions but the change in enthalpy ΔH is a constant quantity. They also discover and employ the additive nature of ΔH.	**5.7**	5.1	5.1, 5.2, 5.3, 15.1
12	*Chemical Equilibrium* Students manipulate variables to explore how to control the direction of a reversible chemical reaction.	**6.9**, 6.10	4.2	7.1, 7.2, 17.2, A.8
13	*Shape of Titration Curves* Students determine the fundamental shape of a titration curve and the parameters that can cause it to change.	1.20, **6.12**, 6.13	4.1, 4.2, 6.4	18.1, 18.4

Activity	Lab Activity	AP Learning Objective	AP Science Practice	IBO Standard
14	*Weak Acid Titration* Students titrate monoprotic and polyprotic weak acids and determine the relationship between the shapes of the curves and the K_a.	6.12, **6.13**	1.4, 5.1	18.1, 18.4
15	*Introduction to Buffers* Students create and analyze a buffer system.	**6.20**	1.4, 6.4	18.2
16	*Buffer Properties* Students analyze the nature of buffers as they prepare buffer solutions of a specified pH and test their efficacy.	**6.18**	4.2, 6.4	18.2
17	*Moving Electrons* By electrolyzing a variety of aqueous solutions, students determine a relationship between current, electric charge, and quantity of electrons.	3.12, **3.13**	4.1, 6.1	9.1, 9.2, 9.5, 19.1, 19.2

MASTER MATERIALS AND EQUIPMENT LIST

Italicized entries indicate items not available from PASCO. The quantity indicated is per student or group. Note: The activities also require protective gear for each student (for example, safety goggles, gloves, apron, or lab coat).

Teachers can conduct some lab activities with sensors and probes other than those listed here. For assistance with substituting compatible sensors and probes for a lab activity, contact PASCO Teacher Support (800-772-8700 inside the United States or http://www.pasco.com/support).

Lab	Title	Materials and Equipment	Qty
1	MODELING CHEMISTRY Students use temperature, pH, and conductivity sensors to explore chemical and physical changes and analyze them for ambiguity while also gaining understanding of sensors and representing reactions at the particulate level.	**MODEL 1** Data Collection System PASCO Temperature Sensor[1] PASCO pH Sensor[1] PASCO Conductivity Sensor[1] *Graduated cylinder, 100-mL* *Beakers (6), glass, 100-mL* *Stirring rod* *Unknowns 1A–1D:* *blue food coloring,* *yellow food coloring,* *0.5 M HCl,* *0.5 M NaOH* *Distilled water wash bottle*	 1 1 1 1 1 1 1 100 mL 1
		MODEL 2 Data Collection System PASCO Absolute Pressure Sensor[1,2] Tubing and tubing connector [1,2] Quick release connector[1,2] Sensor extension cable[2] *Test tube rack* *Test tubes, 20mm × 150 mm, glass* *Rubber stopper, #2, two-hole* *Syringe, 10-mL, to fit stopcock* *Stopcock to fit two-hole stopper* *Graduated cylinder, 10 mL* *Unknown 2A: ethanol* *Unknown 2B: steel wool* *Glycerin* *Tongs* *Paper towel*	 1 1 2 1 1 1 2 1 1 1 1 2 mL ¼ test tube Several drops 1 1
		MODEL 3 Data Collection System PASCO Temperature Sensor[1] PASCO pH Sensor[1] PASCO Conductivity Sensor[1] *Graduated cylinder, 100-mL* *Beaker, glass, 100-mL* *Stirring rod* *Distilled water, 50 mL* *Distilled water wash bottle* *Each group selects one of the following:* *Sucrose ($C_{12}H_{22}O_{11}$),*	 1 1 1 1 1 1 1 1 1 0.5 g

Lab	Title	Materials and Equipment	Qty
		Sodium chloride (NaCl), *Sodium acetate (NaCH$_3$COO),* *Calcium (Ca) metal turning, about the size of half a pea*	
		Ammonium nitrate (NH$_4$NO$_3$)	0.5 g

Lab	Title	Materials and Equipment	Qty

2	LIGHT, COLOR, AND CONCENTRATION
	
	Students use a colorimeter to learn how to use visible light to determine the concentration of colored ion species in a solution
		MODEL 1
		
		Data Collection System
		PASCO Colorimeter
		Cuvette[3]
		Sensor extension cable[3]
		Pipet with pump or bulb, 10-mL
		White 3 × 5 index card or piece of paper
		Colored pencils
		Scissors
		Distilled water and wash bottle
		Kimwipes® or lint free tissues
		One of the following:
		    0.10 M Cobalt(II) nitrate ($Co(NO_3)_2$)
		    0.10 M Nickel(II) nitrate ($Ni(NO_3)_2$)
		    0.10 M Iron(III) nitrate ($Fe(NO_3)_3$)
		    0.10 M Zinc nitrate ($Zn(NO_3)_2$)
			
			1
			1
			1
			1
			1
			1
			1 each
			1
			1
			As needed
			30 mL

		MODEL 2
		
		Data Collection System
		PASCO Colorimeter
		Cuvette[3]
		Sensor extension cable[3]
		Distilled water and wash bottle
		Test tubes, large
		Test tube rack
		Pipet with pump or bulb, 10-mL
		Glass stirring rod
		Kimwipes or lint free tissues
		One of the following:
		    0.10 M Cobalt(II) nitrate ($Co(NO_3)_2$)
		    0.10 M Nickel(II) nitrate ($Ni(NO_3)_2$)
		    0.10 M Iron(III) nitrate ($Fe(NO_3)_3$)
		    0.10 M Copper(II) sulfate ($CuSO_4$)
			
			1
			1
			1
			1
			1
			5
			1
			1
			1
			1
			30 mL

		APPLYING YOUR KNOWLEDGE Data Collection System PASCO Colorimeter Sensor extension cable[3] Cuvette[3] *Pipet with pump or bulb, 10-mL* *Distilled water and wash bottle* *Kimwipes or lint free tissues* *0.10 M Copper(II) nitrate ($Cu(NO_3)_2$)* *Copper(II) nitrate ($Cu(NO_3)_2$), unknown concentration*	 1 1 1 1 1 1 As needed 30 mL 6 mL

Lab	Title	Materials and Equipment	Qty
3	GRAVIMETRIC ANALYSIS Students use a balance and the Solubility Rules to identify an unknown alkali metal carbonate.	**MODEL 1** *Beakers, glass, 100-mL*	4
		Beral pipets	4
		Unknown A (K_2CO_3)	5.0 g
		0.10 M Sodium nitrate, ($NaNO_3$)	5 drops
		0.10 M Potassium chloride, (KCl)	5 drops
		0.10 M Ammonium nitrate, (NH_4NO_3)	5 drops
		0.10 M Calcium chloride, ($CaCl_2$)	5 drops
		Stirring rod	1
		Marking pen (to label beakers)	1
		Distilled water	200 mL
		MODEL 2 AND APPLYING YOUR KNOWLEDGE *Beaker, glass, 100-mL*	1
		Filtration funnel	1
		Erlenmeyer flask, glass, 250-mL	1
		Filter paper, Whatman® Ashless, #42	1
		Watch glass, 100-mm	1
		Analytical balance, 0.001 g precision	1 per class
		Stirring rod	1
		Pencil	1
		Wash bottle with distilled water	1
		Drying oven	1 per class
		MODEL 2 *Unknown A (K_2CO_3)*	1 g
		0.25 M Calcium chloride ($CaCl_2$)	50 mL
		Distilled water	100 mL
		APPLYING YOUR KNOWLEDGE *Unknown B (Li_2CO_3)*	2.00 g
		0.50 M Potassium nitrate (KNO_3)	20 mL
		0.50 M Lithium chloride (LiCl)	20 mL
		0.50 M Calcium nitrate ($Ca(NO_3)_2$)	20 mL
		0.50 M Sodium chloride (NaCl)	20 mL
		Distilled water	As needed

Lab	Title	Materials and Equipment	Qty
4	STOICHIOMETRY OF SOLUTIONS Students use a drop counter, a conductivity sensor, and temperature sensor to determine the concentration of dissolved ions by titration.	**MODELS 1, 2, AND APPLYING YOUR KNOWLEDGE** Data Collection System	1
		PASCO Conductivity Sensor[1]	1
		PASCO High Accuracy Drop Counter	1
		PASCO Fast-response Temperature Sensor	1
		Drop dispenser[4]:	
		Syringe, 60-mL	1
		Stopcock	2
		Drop tip	1
		Beaker, glass, 150-mL	1
		Beaker, 250-mL	1
		Graduated cylinder, 50-mL	1
		Mohr pipet, 25-mL	1
		Pipet pump	1
		Magnetic stirrer (stir plate)	1
		Micro stir bar	1
		Multi clamp	1
		Ring stand	1
		Three-finger clamp	1
		Phenolphthalein	3 drops
		2.0 M Sodium hydroxide (NaOH)	120 mL
		Distilled water	As needed
		Wash bottle	1
		Materials for drop counter and pH sensor calibration (Refer to Appendix A, below)	
		MODEL 1	
		1.0 M Hydrochloric acid (HCl)	25 mL
		MODEL 2	
		Hydrochloric Acid (HCl), one of several possible concentrations	25 mL
		APPLYING YOUR KNOWLEDGE	
		Monoprotic acid of an unknown concentration (HCl is used)	25 mL

Lab	Title	Materials and Equipment	Qty
5	POLAR AND NONPOLAR SUBSTANCES Students use a pH sensor to learn how a compound's structure influences its solubility in water and oil.	**MODEL 1** Data Collection System PASCO pH Sensor[1] *Beaker, 100-mL* *Stirring rod* *Beral pipet* *Mineral oil* *Distilled water* *Colored pencils or camera*	 1 1 5 per class 1 1 30 mL 30 mL As needed
		SET 1 COMPOUNDS *Copper(II) sulfate ($CuSO_4 \cdot 5H_2O$)* *Iron(III) chloride ($FeCl_3$)* *Cobalt(II) chloride ($CoCl_2$)* *NOTE: Use a blender or food processor to shorten preparation time.* *Beta-carotene , ($C_{40}H_{56}$, carrot pigment) from raw carrots* *Capsanthin ($C_{40}H_{56}O_3$, paprika pigment) from powdered paprika* *Riboflavin ($C_{17}H_{20}N_4O_6$, vitamin B) from tablets* *Lycopene ($C_{40}H_{56}$, tomato pigment) from canned tomatoes* *Betanin ($C_{24}H_{27}N_2O_{13}$, beet pigment) from canned beets* *Mineral oil for preparing the solutions* *Ethanol for preparing the solutions*	 0.5 g 0.5 g 0.5 g 10 mL 10 mL 10 mL 10 mL 10 mL 300 mL 150 mL
		SET 2 COMPOUNDS *Acetylsalicylic acid ($C_9H_8O_4$) Aspirin tablets* *Stearic acid ($C_{17}H_{35}COOH$)* *Oleic acid ($C_{17}H_{33}COOH$)* *Acetic acid (CH_3COOH)* *Citric acid ($C_6H_8O_7$)*	 10 mL 0.5 g 10 mL 10 mL 0.5 g
		MODEL 2 *Beaker, 100-mL* *Mineral oil* *Lycopene ($C_{40}H_{56}$, tomato pigment)* *Betanin ($C_{24}H_{27}N_2O_{13}$), beet pigment)*	 2 20 mL 10 mL 10 mL

Lab	Title	Materials and Equipment	Qty
6	SOLUBILITY Students use a conductivity sensor and the mass of dissolved solute to determine the saturation concentration of a compound.	**MODEL 1** Data Collection System PASCO Conductivity Sensor[1] *Beakers, 150-mL* *Balance* *Stirring rod* *Graduated cylinder, 100-mL* *Unknown A, solid (glucose, $C_6H_{12}O_6$)* *Unknown B, solid (potassium bitartrate, $KHC_4H_4O_6$)* *Unknown C, solid (sodium sulfate (Na_2SO_4)* *Distilled water* *Wash bottle with distilled deionized water*	 1 1 3 1 per class 1 1 1.0 g 1.0 g 1.0 g 300 mL 1
		MODEL 2 Data Collection System PASCO Conductivity Sensor *Magnetic stir bar* *Stir plate* *Ring stand* *Graduated cylinder, 100-mL* *Balance (1 per class)* *Beaker, 150-mL* *Clamp* *Potassium bitartrate ($KHC_4H_4O_6$), solid* *Distilled water*	 1 1 1 1 1 1 1 per class 1 1 4.2 g 100 mL
		MODEL 3 *Erlenmeyer flask, 125-mL* *Mohr pipet, 25-mL* *Pipet bulb* *Beaker, 150-mL* *Buret* *Buret clamp* *Funnel* *Quantitative filter paper* *Magnetic stir bar* *Stir plate* *Phenolphthalein* *0.10 M Sodium hydroxide (NaOH)* *Distilled water*	 1 1 1 2 1 1 1 1 1 1 3 drops 80 mL 20 mL

Lab	Title	Materials and Equipment	Qty
7	EMPIRICAL FORMULA Students use a colorimeter and stoichiometric calculations to obtain the chemical formula of a compound.	**MODEL 1** *Hot plate per group or an oven for the class* *Crucible and cover* *Crucible tongs* *Unknown copper hydrate: $CuCl_2 \cdot 2H_2O$* *Balance* **MODEL 2** Data Collection System PASCO Colorimeter Sensor extension cable[3] Cuvette[3] PASCO Conductivity Sensor *Volumetric flask, 100-mL* *Unknown copper hydrate: $CuCl_2 \cdot 2H_2O$* *0.10 M Copper(II) chloride ($CuCl_2 \cdot 2H_2O$), 60 mL* *Distilled water*	1 1 1 1.0 – 1.5 g 1–2 per class 1 1 1 1 1 1 1.0 – 1.5 g 60 mL 25 mL

Lab	Title	Materials and Equipment	Qty
8	MEASURING VITAMIN C —REDOX TITRATION Students use an oxidation reduction potential probe to expand their understanding of titrations, carry out a redox titration, and then use the redox titration method to answer a question of their own design	**MODEL 1** Data Collection System	1
		PASCO Oxidation Reduction Potential (ORP) Probe	1
		Beaker, 250-mL	5 for the class
		Beaker, 150-mL	1
		0.25 % Iodine (I$_2$) solution, from povidone iodine or from solid I$_2$ and KI	50 mL for the class
		0.01 M L-Ascorbic acid (C$_6$H$_8$O$_6$), L-ascorbic acid or vitamin C tablets	50 mL for the class
		3% Hydrogen peroxide (H$_2$O$_2$)	50 mL for the class
		0.01 M Potassium permanganate (KMnO$_4$)	50 mL for the class
		1.0 M Sodium chloride (NaCl)	50 mL for the class
		Distilled water	50 mL
		MODEL 2 AND APPLYING YOUR KNOWLEDGE	
		Data Collection System	1
		PASCO High Accuracy Drop Counter	1
		PASCO Oxidation Reduction Potential (ORP) Probe	1
		Beaker, 150-mL	1
		DROP DISPENSER[4]:	
		Syringe, 60-mL	1
		Stopcock	2
		Drop tip	1
		Multiclamp	1
		Three-finger clamp	1
		Ring stand	1
		Magnetic stir plate and micro stir bar	1
		Analytical balance	1 per class
		Materials for drop counter and pH sensor calibration (Refer to Appendix A below)	
		MODEL 2	
		0.25 % Iodine (I$_2$) solution, from povidone iodine or from solid I$_2$ and KI	70 mL
		L-Ascorbic acid (C$_6$H$_8$O$_6$), L-ascorbic acid or vitamin C tablets	0.040 – 0.060 g
		Distilled water	75 mL
		APPLYING YOUR KNOWLEDGE	
		0.25 % Iodine (I$_2$) solution, from povidone iodine or from solid I$_2$ and KI	As needed
		Foods or juices for vitamin C analysis	As needed
		Juicer	1
		Knife (for slicing fruit)	1

Lab	Title	Materials and Equipment	Qty
9	FACTORS THAT AFFECT REACTION RATE Students use a pressure sensor and temperature sensor to explore several variables that affect the rate of a chemical reaction.	**MODEL 1 AND MODEL 2**	
		Data Collection System	1
		PASCO Temperature Sensor[1]	1
		PASCO Absolute Pressure Sensor[1,2]	1
		Quick-release connector[1,2]	1
		Tubing, 1- to 2-cm[2]	2
		Tubing connectors[2]	2
		Two-hole stopper to fit flask	1
		Erlenmeyer flask, 125-mL	1
		Graduated cylinder, 50-mL	1
		Syringe, 60-mL	1
		Mortar and pestle	1
		MODEL 1	
		Calcium carbonate ($CaCO_3$), solid	0.2 g
		3.0 M Hydrochloric acid (HCl)	1 mL
		Distilled water	50 mL
		MODEL 2	
		Equipment and amounts depend on the variable:	
		Beaker for ice bath	As needed
		Beaker (4), 50-mL	As needed
		Graduated cylinder, 10-mL	As needed
		Magnetic stir bar	As needed
		Stir plate	As needed
		Hot plate	As needed
		Calcium carbonate ($CaCO_3$)	As needed
		3.0 M Hydrochloric acid (HCl)	As needed
		Ice	As needed
		Distilled water	As needed

Lab	Title	Materials and Equipment	Qty
10	**MEASURING THE SPEED OF A REACTION** Students use a colorimeter sensor to determine the order of a reaction and the effect of variables on the reaction rate.	**MODEL 1** Data Collection System PASCO Colorimeter Cuvette[3] Extension cable[3] *Test tubes, 20- to 25-mL* *Volumetric pipets, 10-mL* *Beaker, 50-mL* *5.0×10^{-3} M Crystal violet ($C_{25}H_{30}N_3Cl$)* *0.2 M Sodium hydroxide (NaOH)* *Distilled water for calibration* *Kimwipes or lint free tissues* **MODEL 2** Data Collection System PASCO Colorimeter Sensor PASCO Temperature Sensor[1] Cuvette[3] Extension cable[3] *Beakers (2), 50-mL* *Beakers (2), 400-mL* *Volumetric pipets (2), 10-mL* *0.2 M Sodium hydroxide (NaOH)* *5.0×10^{-3} M Crystal violet ($C_{25}H_{30}N_3Cl$)* *Hot plate* *Ice* *Distilled water for calibration* *Kimwipes or lint free tissues*	 1 1 1 1 2 2 1 10 mL 10 mL 10 mL As needed 1 1 1 1 1 2 2 2 40 mL or as needed 40 mL or as needed 1 1 10 mL As needed

Lab	Title	Materials and Equipment	Qty
11	ENERGY IN CHEMICAL REACTIONS Students use a temperature sensor to demonstrate that the heat q is dependent on reaction conditions but the change in enthalpy ΔH is a constant quantity.	**CALORIMETER FOR MODEL 1, MODEL 2, MODEL 3, AND APPLYING YOUR KNOWLEDGE**	
		Data Collection System	1
		PASCO Stainless Steel Temperature Sensor[1]	1
		Polystyrene cup, 8 oz	1
		Ring stand	1
		Beaker, 250-mL	1
		Clamp, utility	1
		Graduated cylinder, 50-mL or 100-mL	1
		10 cm × 10 cm cardboard lid	1
		MODEL 1	
		Ammonium nitrate (NH_4NO_3), solid	2, 4, or 6 g
		Distilled water	50 or 100 mL
		MODEL 2	
		1.0 M Sodium hydroxide (NaOH)	100 mL
		1.0 M Hydrochloric acid (HCl)	100 mL
		Distilled water	100 mL
		MODEL 3	
		1.0 M Sodium hydroxide (NaOH)	100 mL
		1.0 M Hydrochloric acid (HCl)	100 mL
		Sodium hydroxide (NaOH)	4 g
		APPLYING YOUR KNOWLEDGE	
		2.0 M Hydrochloric acid (HCl)	100 mL
		Magnesium ribbon (Mg)	About 0.5 g

Lab	Title	Materials and Equipment	Qty
12	CHEMICAL EQUILIBRIUM Students use the results of a colorimeter and a temperature sensor to control the direction of a reversible chemical reaction.	**MODEL 1** Data Collection System PASCO Colorimeter Extension cable[3] Cuvettes[3] Beakers, 50-mL Mohr pipet, 10-mL Pipet bulb 0.0080 M Iron(III) nitrate (Fe(NO$_3$)$_3$·9H$_2$O) 0.0010 M Potassium thiocyanate (KSCN) Kimwipes or lint free tissues	 1 1 1 3 3 1 1 3.0 mL 3.0 mL As needed
		MODEL 2 Test tube rack Distilled water Plastic pipets Test tubes, 19 × 150 mm (medium) Gloves Marking pen(to label beakers) Cobalt chloride (CoCl$_2$·6H$_2$O) 0.10 M Silver nitrate (AgNO$_3$) 6.0 M Hydrochloric acid (HCl) Scoop Glass stirring rod	 1 2 mL 3 3 1 pair 1 1.5 g 2 mL 2 mL 1 1
		MODEL 3 Data Collection System PASCO Fast-response Temperature Sensor Beakers(2), 250-mL Hot plate Cobalt solution from Model 2 Water for water baths Ice	 1 1 2 1 1 As needed As needed

		APPLYING YOUR KNOWLEDGE
		
		Data Collection System
		PASCO Colorimeter
		Extension cable[3]
		Cuvettes[3]
		Mohr pipet, 10-mL
		Pipet bulb
		Equipment and amounts depend on the procedure:
		   Test tube, 19 × 150 mm (medium)
		   Beakers, 50-mL
		   Graduated cylinder, 10-mL
		   0.0010 M Potassium thiocyanate (KSCN)
		   0.0080 M Iron(III) nitrate (Fe(NO$_3$)$_3$)[1]
		Kimwipes or lint free tissues
			
			1
			1
			1
			As needed
			1
			1
			
			As needed
			As needed
			As needed
			As needed
			As needed
			As needed

Lab	Title	Materials and Equipment	Qty

13	SHAPE OF TITRATION CURVES
	
	Students use a pH Sensor and drop counter to determine the fundamental shape of a titration curve and the parameters that can cause it to change.
		MODELS 1, 2, AND APPLYING YOUR KNOWLEDGE
		Data Collection System
		PASCO pH Sensor[1]
		PASCO High Accuracy Drop Counter
		Drop dispenser[4]:
		    Syringe, 60-mL
		    Stopcock
		    Drop tip
		Beaker, glass, 150-mL
		Beaker, 250-mL
		Mohr pipet, 25-mL
		Pipet pump
		Magnetic stirrer (stir plate)
		Micro stir bar
		Multi clamp
		Ring stand
		Three-finger clamp
		Distilled water
		Wash bottle
		Materials for drop counter and pH sensor calibration
		    (Refer to Appendix A, below)
			
			1
			1
			1
			
			1
			2
			1
			1
			1
			1
			1
			1
			1
			1
			1
			1
			As needed
			1

		MODEL 1 *0.10 M Sodium hydroxide (NaOH)* *0.10 M Hydrochloric acid (HCl)* *Phenolphthalein ($C_{20}H_{14}O_4$) indicator solution*	 260 mL 20 mL 2 drops
		MODEL 2 *0.10 M Sodium hydroxide (NaOH)* *0.10 M Hydrochloric acid (HCl)* *0.05 M Hydrochloric acid (HCl)* *0.025 M Hydrochloric acid (HCl)* *0.10 M Acetic acid (CH_3COOH)* *0.10 M Potassium hydrogen tartrate ($KC_4H_5O_6$),*	 260 mL 20 mL 20 mL 20 mL 20 mL 20 mL
		APPLYING YOUR KNOWLEDGE *0.10 M Sodium hydroxide (NaOH)* *Unknown acid of unknown concentration (0.2 M HCl)*	 260 mL 15 mL

Lab	Title	Materials and Equipment	Qty
14	WEAK ACID TITRATION Students use a drop counter and pH sensor to titrate monoprotic and polyprotic weak acids and determine the relationship between the shapes of the curves and K_a.	**MODEL1, MODEL 2, AND APPLYING YOUR KNOWLEDGE** Data Collection System	
			1
		PASCO pH Sensor[1]	1
		PASCO High Accuracy Drop Counter	1
		Drop dispenser[4]:	
		Syringe, 60-mL	1
		Stopcock	2
		Drop tip	1
		Beaker, glass, 150-mL	1
		Beaker, 250-mL	1
		Mohr pipet, 25-mL	1
		Pipet pump	1
		Magnetic stirrer (stir plate)	1
		Micro stir bar	1
		Pipet pump	1
		Multi clamp	1
		Ring stand	1
		Three-finger clamp	1
		0.5 M Sodium hydroxide	160 mL
		Distilled water	As needed
		Wash bottle	1
		Materials for drop counter and pH sensor calibration (Refer to Appendix A, below)	
		MODEL 1	
		1.0 M Acetic acid (CH₃COOH)	20 mL
		MODEL 2	
		0.05 M Maleic Acid (C₃H₄O₄)	50 mL
		APPLYING YOUR KNOWLEDGE	
		Aspirin	1
		Mortar and Pestle	1

Lab	Title	Materials and Equipment	Qty
15	INTRODUCTION TO BUFFERS Students use a pH sensor to create and analyze a buffer system.	**MODEL 1**	
		Data Collection System	1
		PASCO pH sensor[1]	1
		Beaker (glass), 50-mL	1
		Graduated cylinder 25-mL	1
		Acetic acid (CH_3COOH)	20 mL
		Sodium acetate ($NaCH_3COO$)	Approx. 1 g
		Stirring rod	1
		Scoopula™ spatula	1
		Materials for drop counter and pH sensor calibration (Refer to Appendix A, below)	
		MODEL 2	
		Data Collection System	1
		PASCO pH sensor[1]	1
		Beakers, 50-mL	5
		Graduated cylinder, 25-mL	1
		Graduated cylinder, 10-mL or volumetric pipet, 5-mL	1
		Solution 1: Distilled water	20 mL
		Solutions 2–4, below, are prepared with 1.0 M Acetic acid, sodium bisulfate, sodium bicarbonate, and sodium hydroxide	
		Solution 2: 0.01 M Acetic acid (CH_3COOH)	20 mL
		Solution 3: 0.01 M Acetic acid (CH_3COOH) and 0.01 M Sodium acetate ($NaCH_3COO$)	20 mL
		Solution 4: 0.01 M Sodium bisulfate ($NaHSO_3$) and 0.01 M Sodium sulfate (Na_2SO_3)	20 mL
		Solution 5: 0.01 M Sodium bicarbonate ($NaHCO_3$) and 0.01 M Sodium carbonate (Na_2CO_3)	20 mL
		0.01 M Sodium hydroxide ($NaOH$)	25 mL
		Stirring rod	1
		Wash bottle	1
		APPLYING YOUR KNOWLEDGE	
		Data Collection System	1
		PASCO pH sensor	1
		Beakers, 100-mL	2
		Stirring rod	1
		Bufferin™ tablet, 325 mg	1
		Aspirin tablet, 325 mg	1
		Mortar and pestle	1
		Distilled water	100 mL

Lab	Title	Materials and Equipment	Qty
16	BUFFER PROPERTIES Students use a pH sensor to analyze the nature of buffers as they prepare buffer solutions of a specified pH and test their efficacy.	**MODEL 1** Data Collection System PASCO pH Sensor[1] *Analytical balance* *Volumetric flask, 100-mL or 250-mL* *Beakers, glass, 50-mL* *Sodium acetate ($NaCH_3COO$)* *Ammonium chloride (NH_4Cl)* *0.3 M Acetic acid (CH_3COOH)* *0.3 M Ammonia (NH_3), formulated from NH_4OH* *Distilled water* *Marking pen (to label beakers)*	 1 1 1 1 2 Approx. 1 g Approx. 1 g 100 mL 100 mL 150 mL 1
		MODEL 2 *Universal indicator* *Beral pipets* *Test tubes, 20 mm × 150 mm, glass, 25-mL* *0.10 M Hydrochloric acid (HCl)* *0.10 M Sodium hydroxide (NaOH)* *Buffer solution from Model 1* *Distilled and deionized water*	 4 drop 2 3 20 mL 20 mL 10 drops 50 mL

		APPLYING YOUR KNOWLEDGE
		Data Collection System
		PASCO pH sensor[1]
		Beakers, 50-ml
		Volumetric flask, 100-ml
		Two of the following, to create 100 mL of buffer:
		    0.3 M Acetic acid (CH_3COOH)
		    0.3 M Sodium acetate ($NaCH_3COO$)
		    0.3 M Sodium phosphate dibasic (Na_2HPO_4)
		    0.3 M Sodium phosphate monobasic (NaH_2PO_4)
		    0.3 M Ammonia (NH_3) from NH_4OH
		    0.3 M Ammonium chloride (NH_4Cl)
		    0.3 M Potassium phosphate (K_3PO_4)
		    0.3 M Phosphoric acid (H_3PO_4)
		6 M Sodium hydroxide (NaOH)
		6 M Hydrochloric acid (HCl)
		Stirring rod
			
			1
			1
			2
			1
			50 mL of
			each used
			
			5 drops
			5 drops
			1

Lab	Title	Materials and Equipment	Qty
17	MOVING ELECTRONS Students use a voltage–current sensor to electrolyze a variety of aqueous solutions to determine a relationship between current, electric charge, and quantity of electrons.	**ALL MODELS** Data Collection System PASCO Voltage–Current Sensor Wire leads (included with Voltage-Current Sensor)	 1 1 2 red, 1 black
		Electrodes *Alligator clips*	2 2 red, 2 black
		9 V Battery *9 V Battery cap with leads* *Beaker, glass, 400-mL* *Stirring rod* *Wash bottle with distilled water*	1 1 1 1 1
		MODEL 1 *Test tubes (2), 10 mm × 75-mm* *Universal indicator* *Scoopula™ spatula* *Epsom salt (Magnesium sulfate, $MgSO_4$), 4–6 marble-size scoops (one scoop is approximately 3 g)* *Distilled water*	 2 20 drops 1 As specified 600 mL
		MODEL 2 *Potassium iodide, KI, 1 marble-size scoop (one scoop is approximately 3 g)* *Scoopula™ spatula* *Copper(II) bromide, ($CuBr_2$), 1 marble-size scoop (one scoop is approximately 3 g)* *Distilled water*	 As specified As specified 600 mL
		MODEL 3 *Copper strip* *Steel wool* *Metals strip, spoon, or key* *1.0 M Copper(II) sulfate ($CuSO_4$)* *Analytical balance*	 1 1 1 100 mL 1 per class
		APPLYING YOUR KNOWLEDGE *Copper strip* *Steel wool* *Metal strip, spoon, or key* *1.0 M Copper(II) sulfate, ($CuSO_4$)* *Analytical balance*	 1 1 1 100 mL 1 per class

Lab	Title	Materials and Equipment	Qty
A	APPENDIX A: SENSOR CALIBRATION	**CALIBRATING A DROP COUNTER**	
		Data Collection System	1
		PASCO High Accuracy Drop Counter	1
		Drop dispenser:	
		Syringe, 60-mL	1
		Stopcock (2)	2
		Drop tip	1
		Graduated cylinder, 10-mL	1
		Beaker, for waste	1
		Multi clamp	1
		Ring stand	1
		Three-finger clamp	1
		Titrant	> 10 mL
		CALIBRATING A pH SENSOR	
		Data Collection System	1
		PASCO pH Sensor	1
		Buffers, pH 4 and pH 10	1 of each

[1]Included with PASCO Advanced Chemistry Sensor

[2]Included with most PASCO Absolute Pressure Sensors

[3]Included with PASCO Colorimeter

[4]Included with PASCO Drop Counter

ACTIVITY BY PASCO SENSORS

This list shows the sensors used in each lab activity.

Items Available from PASCO	Qty	Activity Where Used
PASCO Absolute Pressure Sensor[1]	1	1, 9
PASCO Colorimeter	1	2, 7, 10, 12
PASCO Conductivity Sensor[1]	1	1, 4, 6
PASCO High Accuracy Drop Counter	1	4, 8, 13, 14
PASCO pH Sensor[1]	1	1, 5, 13, 14, 15, 16
PASCO Oxidation Reduction Potential (ORP) Probe	1	8
PASCO Fast-response Temperature Sensor	1	4, 12
PASCO Stainless Steel Temperature Sensor[1]	1	11
PASCO Temperature Sensor[2]	1	1, 9, 10
PASCO Voltage–Current Sensor	1	17

[1]This sensor is part of the PASCO Advanced Chemistry Sensor.

[2]In this lab either the fast-response temperature sensor or the stainless steel temperature sensor can be used.

NORMAL LABORATORY SAFETY PROCEDURES

Disclaimer

Regarding chemical safety, some of the substances and chemicals referred to in this manual are regulated under various safety laws (local, state, national, or international). PASCO scientific does not purport in this manual, or in any other publication, to specify minimum safety or legal standards associated with the handling of hazardous chemicals, their use, their disposal, or the methods prescribed by using them in laboratories or classrooms.

Teachers and administrators should refer to their school's or district's laboratory safety procedures. They should consult with legal counsel or other professional advisers about the applicable laws, safety issues, and compliance issues for storing and disposal of chemicals and the methods for use in school classrooms and laboratories.

As a reference, the Occupational Safety and Health Administration (www.osha.gov) of the Department of Labor, United States offers the *School Chemistry Laboratory Safety Guide* for information about important components of safety in the chemistry laboratory and is a resource to locate further information.

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1. MODELING CHEMISTRY

Initial Question

Exploring chemical and physical changes in a laboratory experiment is not as easy as one may think. The general appearance of a substance can tell us something about events on the molecular level, but this provides limited information. Measuring parameters like conductivity, temperature, pH, or pressure with digital sensors can provide data that helps us understand more about what is going on, but even that may not be enough to completely understand that which is too small to see. This is the challenge of being a chemist.

What tools allow us to examine physical and chemical changes?

Learning Objectives[*]

Students compare various physical and chemical changes and analyze them for ambiguity while also gaining understanding of sensors and representing reactions at the particulate level

LO 2.3 / The student is able to use aspects of particulate models (i.e., particle, spacing, motion and forces of attraction) to reason about observed differences between solid and liquid phases and among solid and liquid materials.

LO 2.5 / The student is able to refine multiple representations of a sample of mater in the gas phase to accurately represent the effect of changes in macroscopic properties on the sample.

LO 3.1 / Students can translate among macroscopic observations of change, chemical equations and particle views.

LO 3.10 / The student is able to evaluate the classification of a process as a physical change, chemical change, or ambiguous change based on both macroscopic observations and the distinction between rearrangement of covalent interactions and noncovalent interactions.

LO 5.10 / The student can support the claim about whether a process is a chemical or physical change (or may be classified as both) based on whether the process involves changes in intramolecular versus intermolecular interactions.

SP 1.1 / The student can *create representations and models* of natural or man-made phenomena and systems in the domain.

SP 1.3 / The student can *refine representations and models* of natural or man-made phenomena and systems in the domain.

SP 1.4 / The student can *use representations and models* to analyze situations or solve problems qualitatively and quantitatively.

SP 4.3 / The student can *collect data* to answer a particular scientific question.

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

SP 5.3 / The student can *evaluate the evidence provided* by data sets in relation to a particular scientific question.

SP 6.1 / The student can *justify claims with evidence*.

SP 6.2 / The student can *construct explanations of phenomena based on evidence* produced through scientific practices.

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

SP 7.1 / The student can *connect phenomena and models* across spatial and temporal scales.

Time Requirement

Preparation time: 20 minutes / Lab activity: 90 minutes

Materials and Equipment

Model 1

- Data collection system
- Temperature sensor[1]
- pH sensor[1]
- Conductivity sensor[1]
- Graduated cylinder, 100-mL
- Beakers (6), glass, 100-mL
- Stirring rod
- Unknowns 1A–1D , 100 mL each[2]
- Distilled water wash bottle

[1]Included with the PASCO Advanced Chemistry Sensor.

[2]To formulate the unknowns, refer to the Lab Preparation section (Unknown 1A: Distilled water with blue food coloring; Unknown 1B: Distilled water with yellow and red food coloring; Unknown 1C: 0.5 M HCl; Unknown 1D: 0.5 M NaOH).

Model 2

- Data collection system
- Absolute pressure sensor[1,3]
- Tubing and tubing connector (2)[1,3]
- Quick release connector[1,3]
- Sensor extension cable[3]
- Test tube rack
- Test tubes (2), 20mm × 150 mm, glass
- Rubber stopper, #2, two-hole
- Syringe, 10-mL, to fit stopcock
- Stopcock to fit two-hole stopper
- Graduated cylinder, 10 mL
- Unknown 2A, 2 mL[2]
- Unknown 2B , fill approximately 1/4 of the test tube[2]
- Glycerin, several drops
- Tongs
- Paper towel

[1]Included with the PASCO Chemistry Sensor.

[2]To formulate the unknowns, refer to the Lab Preparation section (Unknown 2A: Ethanol; Unknown 2B: Steel wool).

[3]Included with most PASCO Absolute Pressure sensors.

Model 3

- Data collection system
- Temperature sensor[1]
- pH sensor[1]
- Conductivity sensor[1]
- Graduated cylinder, 100-mL
- Beaker, glass, 100-mL
- Stirring rod
- Distilled water, 50 mL
- Distilled water wash bottle
- Each group is assigned one of the following::

  Sucrose ($C_{12}H_{22}O_{11}$), about 0.5 g

  Sodium chloride (NaCl), about 0.5 g

  Sodium acetate ($NaCH_3COO$), about 0.5 g

  Calcium (Ca) metal turning, about the size of half a pea

  Ammonium nitrate (NH_4NO_3), about 0.5 g

[1]Included with the PASCO Advanced Chemistry Sensor.

Prerequisites

Students should be familiar with the following concepts:

- Kinetic molecular theory
- Brønsted and Lowry definition of acids and bases

Lab Preparation

These are the materials and equipment to set up prior to the lab:

Model 1

1. **Unknown 1A:** Distilled water mixed with a few drops of blue food coloring. Try to make the solution match the color of a copper(II) sulfate solution so it is not obvious that food coloring was used.

2. **Unknown 1B:** Distilled water mixed with a few drops of yellow food coloring. Try to make the solution match the color of an iron(III) chloride solution by adding a drop of red food coloring so that it is not obvious that food coloring was used.

3. **Unknown 1C:** 0.5 M HCl. Obtain a 1000-mL volumetric flask. Fill the flask half full with distilled water. Carefully add 41.0 mL of concentrated stock HCl (12 M) to the flask. Continue adding distilled water to the 1000-mL mark.

4. **Unknown 1D:** 0.5 M NaOH. Obtain a 1000-mL volumetric flask. Fill the flask half full with distilled water. Add 20.0 g of NaOH pellets to the flask. Swirl to dissolve. Continue adding distilled water to the 1000-mL mark.

Model 2

5. **Unknown 2A:** Ethanol. Each student group will need 2.0 mL. No additional preparation is needed.

6. **Unknown 2B:** Steel wool. Stretch the steel wool apart to increase the surface area and break it into several small samples (enough to fill one quarter of the test tube). Soak the steel wool in a beaker of vinegar. Keep the samples in vinegar in a large beaker for students to remove with tongs during the lab.

Model 3

7. In this model, five reactions are to be carried out. Assign one reaction to each student group so all reactions are performed. Students share the data for the reactions they haven't done.

All Models

8. Set up various waste containers for the disposal of the unknowns. Group them by hazard or disposal method.

Safety

Add these important safety precautions to your normal laboratory procedures:

*   Treat all unknowns as a hazardous, toxic, and harmful material.

*   All unknowns should be disposed of in the proper waste container.

*   Some of the unknowns in this lab are flammable. No unknowns should be used around an open flame.

Getting Your Brain in Gear

1. In this lab you use a temperature probe. Consider the following particulate-level representations. Which beaker contains the hot water and which contains the cold water? Explain your reasoning.
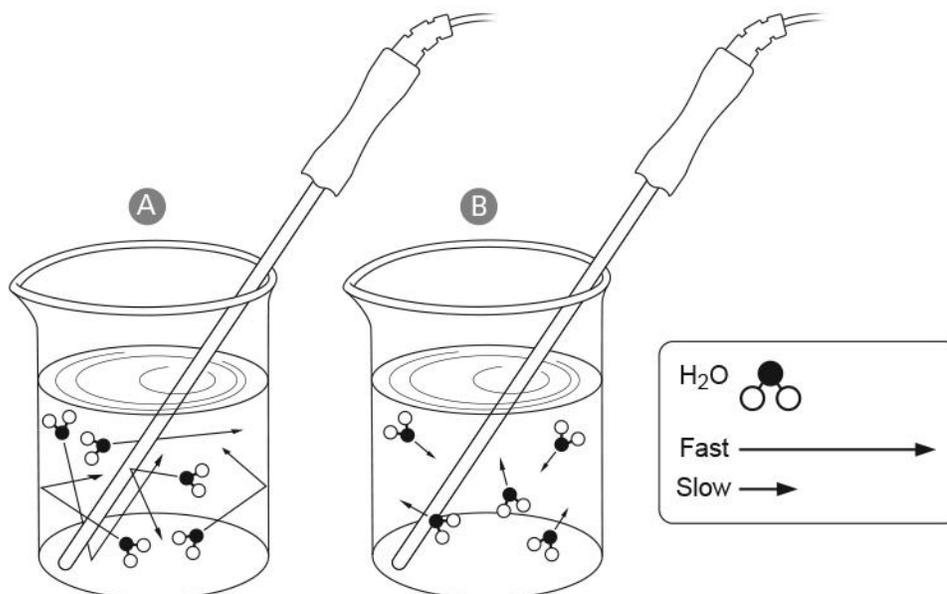
Beaker A contains hot water and Beaker B contains cold water. Temperature is a function of average particle speed, so the greater the speed, the higher the temperature.

2. In this lab you use a pH sensor. Consider the following particulate-level representations. Label the beakers as "Acid", "Base", or "Neutral". Explain your reasoning.
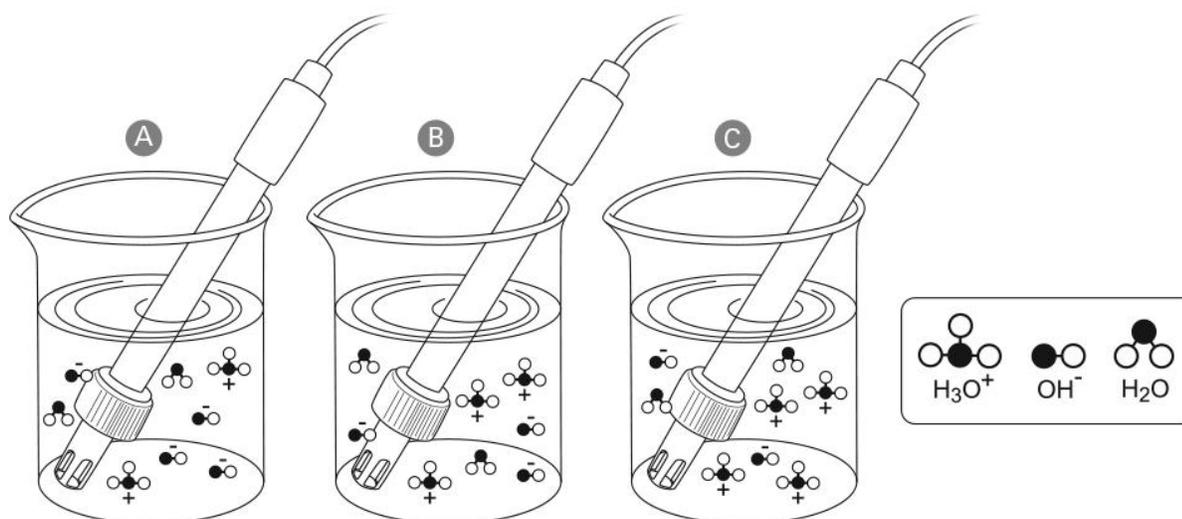
Beaker A should be labeled "Base", Beaker B should be labeled "Neutral", and Beaker C should be labeled "Acid" because pH is a measurement of H_3O^+ ions. The more H_3O^+ ions present in the solution, the more acidic the solution. A solution with the same number of H_3O^+ ions as OH^- ions is a neutral solution, and one with fewer H_3O^+ ions than OH^- ions is a base.

3. In this lab you also use a conductivity sensor. Consider the following particulate-level representations. Label the beakers as "Low conductivity", "Medium conductivity", or "High conductivity". Explain your reasoning.
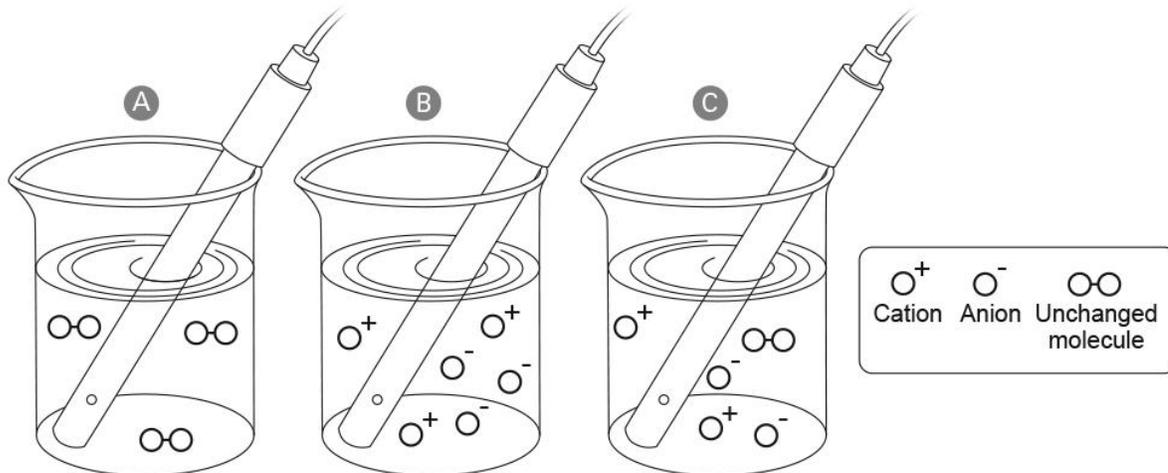
Beaker A should be labeled "Low conductivity," Beaker B should be labeled "High conductivity," and Beaker C should be labeled "Medium conductivity" because conductivity is a measurement of the number of ions in solution.

4. Finally, in this lab you use a pressure sensor. Consider the following particulate-level representations. Label the tubes as "High pressure" or "Low pressure". Explain your reasoning.
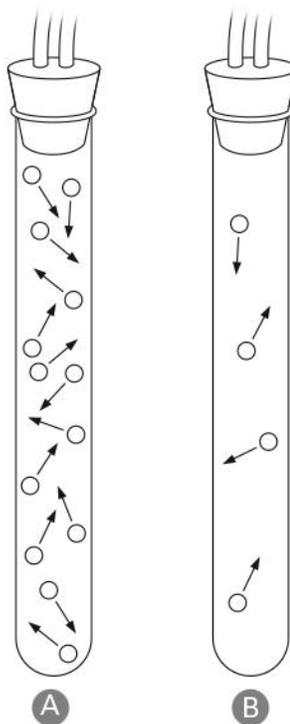
Test Tube A should be labeled "High pressure" and Test Tube B should be labeled "Low pressure" because a gas sample in the same sized container, but with fewer molecules (fewer collisions with the sides of the container) has less pressure.

5. Analyze the following particulate-level representations of different processes.

i.

——	Intramolecular forces or bonds
·········	Intermolecular forces or bonds
←	Motion (moving particle)

ii.

iii.

iv.
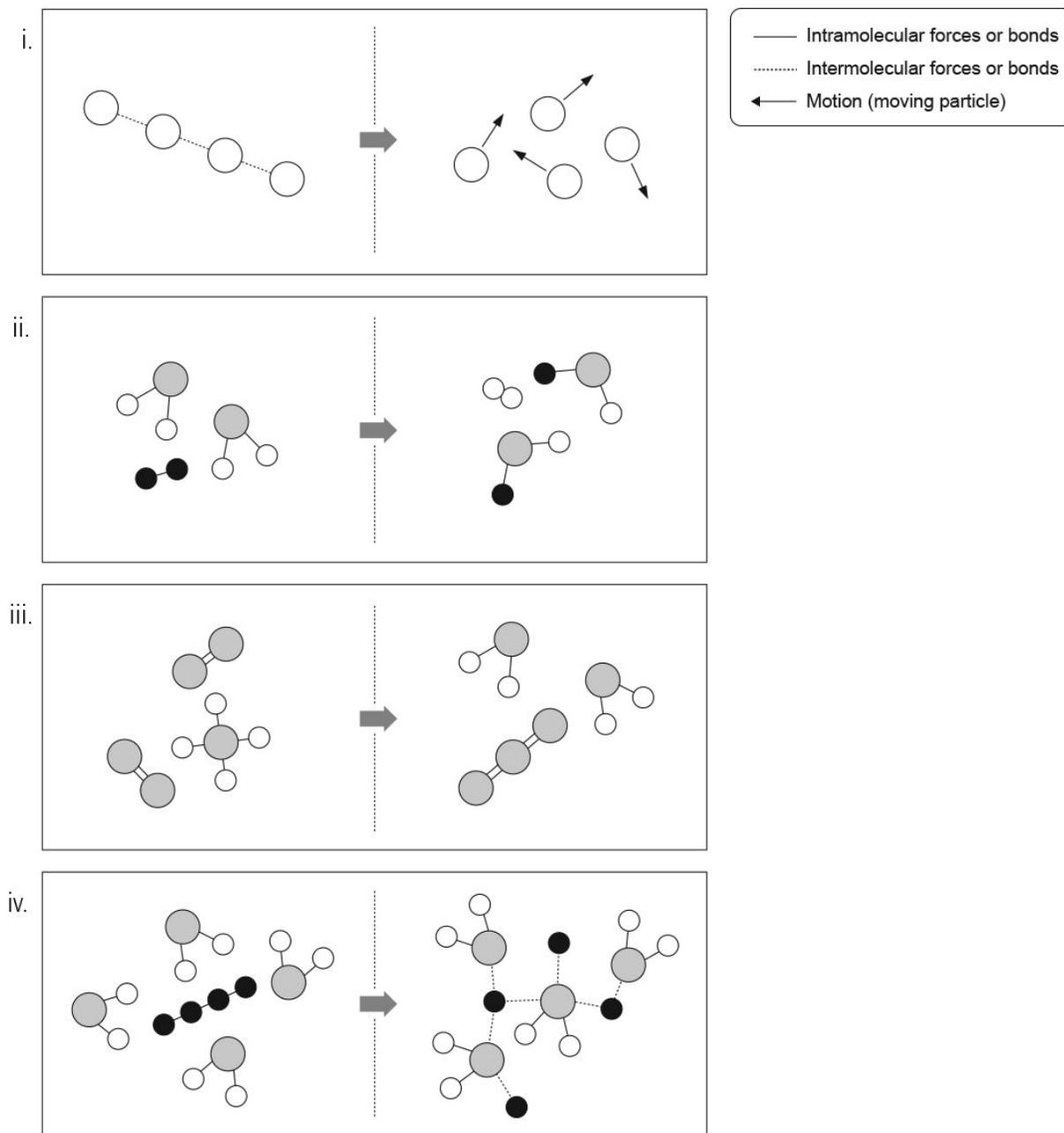
a. Which representations above show a change in both intramolecular bonds and intermolecular forces?

iv. Intramolecular bonds (shown in the diagram on the left) are broken and intermolecular forces are formed (shown in the diagram on the right).

b. Which representations above show a change in just intramolecular bonds? Justify your answer.

ii and iii. The rearrangement of atoms in a molecule is a clue that intramolecular bonds have changed.

c. Which representations above show a change in just intermolecular forces? Justify your reasoning.

i. Intermolecular forces (shown in the diagram on the left) are broken and no bonds are created.

MODEL 1

Building Model 1 – Is it a Chemical Change?

1. Obtain 6 clean 100-mL beakers and label them "A", "B", "C", "D", "AB", and "CD".

2. Pour 100 mL of Unknown 1A into Beaker A.

3. Pour 100 mL of Unknown 1B into Beaker B.

4. Pour 100 mL of Unknown 1C into Beaker C.

5. Pour 100 mL of Unknown 1D into Beaker D.

6. Combine 50 mL of Unknown 1A from Beaker A and 50 mL of Unknown 1B from Beaker B into Beaker AB. Note any visible changes that occur.

7. Combine 50 mL of Unknown 1C from Beaker C and 50 mL of Unknown 1D from Beaker D into Beaker CD. Note any visible changes that occur.

❷ 8. Observe Beakers AB and CD. Only one represents a chemical change. Speculate as to which beaker, AB or CD, represents a chemical change. Explain your reasoning.

   At this point students may indicate that Beaker AB was a chemical change because the color changed. They will probably indicate that Beaker CD was not a chemical change because nothing was observed. Although this is incorrect, they should be allowed to make that prediction. Further observation will clarify the changes later in the lab activity.

❷ 9. With your lab group, brainstorm how temperature, pH, and conductivity sensors could be used to determine which beaker underwent a chemical change.

   Answers will vary. Students should suggest that temperature, pH, and conductivity be recorded for the reactant beakers (A, B, C, and D) and the product beakers (AB and CD) and then compared. A large change in temperature, conductivity, or pH could indicate a change in intramolecular bonds, and thus a rearrangement of atoms in the solutions.

10. Start a new experiment on the data collection system.

11. Connect the pH sensor to the data collection system.

12. Calibrate the pH sensor.

13. Connect the temperature sensor to the data collection system.

14. Connect the conductivity sensor to the data collection system.

15. Display a digital readout of temperature, pH, and conductivity on the data collection system.

16. Empty Beakers AB and CD and rinse them thoroughly with distilled water.

17. Record observations of color, temperature, pH, and conductivity of the reactant beakers (A–D) by inserting the sensors into each beaker. Rinse the sensors between measurements with distilled water from a wash bottle. Record the data in the Model 1 Data Table.

18. Use the remaining solutions in Beakers A–D to repeat the reactions carried out above by combining the solutions in Beakers A and B and making measurements, and then combining the solutions in Beakers C and D and making measurements. Record observations of color, temperature, pH, and conductivity for both product Beakers AB and CD immediately after the reactants are mixed by inserting the sensors into each beaker. Rinse the sensors between measurements with distilled water. Record the data in the Model 1 Data Table.

Model 1 – Is it a Chemical Change?

Table 1: Model 1 Data Table—Determining a chemical change

Reactant Beaker	Color	pH	Temperature (°C)	Conductivity (Low/Med/High)
A	Blue	7	25	Low
B	Yellow	7	25	Low
AB	Green	7	25	Low
C	Colorless	3	25	High
D	Colorless	13	25	High
CD	Colorless	7	30	Med

For conductivity:
    Low: Less than 100 μS/cm
    Med: Between 100 μS/cm and 1000 μS/cm
    High: Greater than 1000 μS/cm

Analyzing Model 1 – Is it a Chemical Change?

19. Which reaction, the one in Beaker AB or the one in Beaker CD, showed a greater change in temperature, conductivity, and pH?

Beaker CD showed a greater change in all three measurements.

20. When a large change in temperature is observed during a reaction, what might be occurring on the molecular level in the beaker?

A large temperature change indicates the breaking or forming of intramolecular bonds.

21. When a large change in conductivity is observed during a reaction, what might be occurring on the molecular level in the beaker?

A large conductivity change indicates that ions are either being formed from neutral species or that ions are combining to form neutral species.

22. When a large change in pH is observed during a reaction, what might be occurring on the molecular level in the beaker?

A large pH change indicates that H_3O^+ ions are either being formed or being used in a chemical reaction. If the pH moves towards a more neutral reading, the H_3O^+ ions are combining with OH^- ions to make H_2O.

23. Analyze the particulate-level representations below and answer the following questions.
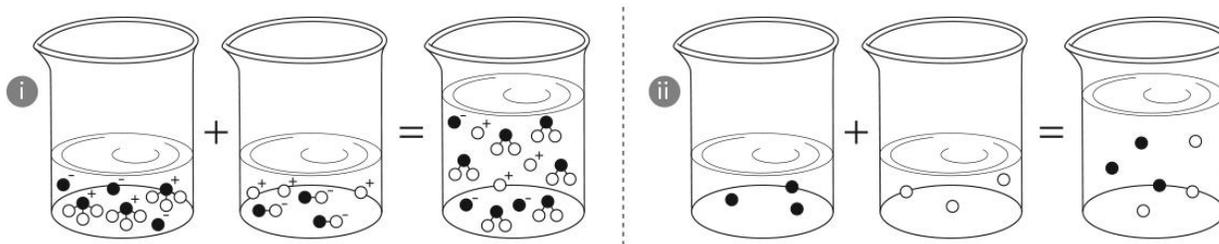
a. Which set of particulate-level representations matches the data for mixing the solution in Beaker A with the solution in Beaker B to produce the products in Beaker AB? Explain your reasoning based on the sensor data.

Diagram ii represents A + B → AB best because there is no change in charges of the ions, so there is no significant change in conductivity. No change in H_3O^+ or OH^- concentrations is shown, so there is no significant change in the pH. No intramolecular bonds are formed or broken, so there should be no significant change in temperature. This fits the unchanged values of these parameters in Beaker AB.

b. Which set of particulate-level representations matches the data for mixing the solution in Beaker C with the solution in Beaker D to produce the products in Beaker CD? Explain your reasoning based on the sensor data.

Diagram i represents C + D → CD best because there are more ions in the reactant beakers than in the product beaker, which would result in a decrease in conductivity. The H_3O^+ ions in the first beaker would produce a low pH reading and the OH^- ions in the second beaker would produce a high pH reading. The final beaker has fewer H_3O^+ and OH^- ions in it, which would result in a more neutral pH. The formation of intramolecular bonds when the H_3O^+ and OH^- ions combine would release energy, which would result in a temperature increase. This is consistent with the data for Beaker CD.

24. A change in color can be a clue that chemical change is occurring. Was that the case in Model 1? Justify your answer with data from Model 1.

No. The reaction A + B → AB changed color, but the sensors did not give any supporting evidence that a chemical change occurred.

25. Based on the particulate-level representations and sensor data collected, put a check by all the traits of a chemical change.

         a. Substance(s) remain unchanged.

   ✓   b. Atoms within molecules and compounds rearrange.

   ✓   c. Chemical properties of products are different than reactant properties.

         d. Chemical properties of products remain the same as reactant properties.

   ✓   e. Bonds are made or broken.

26. With your lab group, create a one-sentence definition of a chemical change.

Answers will vary but should include: Atoms within molecules and compounds rearrange, chemical properties of products are different from reactant properties, and bonds are made or broken.

MODEL 2

Building Model 2 – Chemical versus Physical Change

1. Start a new experiment on the data collection system.

2. Connect the absolute pressure sensor to the data collection system using a sensor extension cable.

3. Connect the quick-release connector to the stopper using the tubing connector and the 1- to 2-cm piece of tubing by following the steps below. Use the picture as a guide.
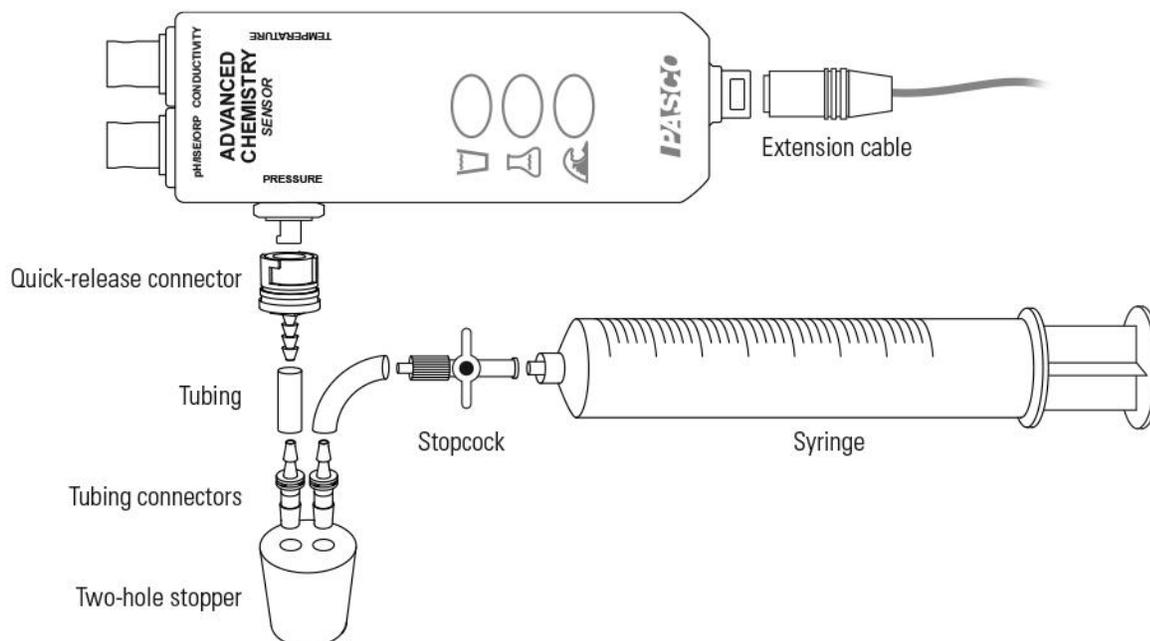
    a. Insert the thicker end of one of the tubing connectors into the hole in the stopper. If this is difficult, add a drop of glycerin.

    b. Connect a 1- to 2-cm piece of tubing to the other, thinner end of the tubing connector.

    c. Insert the barbed end of the quick-release connector into the open end of the 1- to 2-cm piece of tubing. If this is difficult, add a drop of glycerin.

4. Insert the quick-release connector into the port of the absolute pressure sensor and then turn the connector clockwise until the fitting "clicks" onto the sensor (about one-eighth turn).

5. Display a pressure versus time graph on the data collection system.

6. Obtain two test tubes. Label them "A" and "B". Place them into a test tube rack.

7. Connect the syringe to the stopper as shown in the diagram and insert the stopper into Test Tube A. Start collecting data.

8. Using the syringe, obtain a 2 mL sample of Unknown 2A. Open the stopcock, quickly inject the sample, and pull the plunger back to the 2-mL mark.

9. Observe the change in pressure. Record if the pressure increased, decreased, or stayed the same over a 1-minute time interval in the Model 2 Data Table. Note any visible gas formation.

10. Remove the stopper and return the test tube to the test tube rack. Stop collecting data on the data collection system.

11. In the procedure just performed, you removed 2 mL of gas (mostly air) from the test tube after introducing the liquid. Explain why that step was necessary in order to keep the initial gas pressure constant.

    The introduction of 2 mL of liquid reduces the volume occupied by gas in the test tube and increases the pressure. To keep the initial gas pressure constant, a volume of gas equal to that of the introduced liquid needed to be removed.

❷ 12. Using the particulate-level representations provided in the Getting Your Brain in Gear questions as a guide, draw gas molecules in the "Final" test tube to represent the pressure change you observed.

❷ 13. Explain how the pressure data collected helped you determine what happened in Test Tube A.

    The data indicated that the final pressure was greater than the initial pressure. As there was no change in volume, the increase in pressure must have resulted from an increase in the number of gas particles. (Temperature was not measured, so no conclusion based on any change in temperature can be made.)

14. Take Test Tube B and, with tongs, fill the test tube one quarter full of Unknown 2B. Dry it with a paper towel and immediately place it inside Test Tube B. Be careful not to compress the unknown.

15. Remove the syringe and turn the stopcock to the closed position. Insert the stopper connected to the pressure sensor into the test tube and immediately start collecting data.

16. Observe the change in pressure. Record if the pressure increased, decreased, or stayed the same over a 10-minute time interval in Model 2. Note any visible gas formation and color change.

17. Stop collecting data on the data collection system. Remove the stopper and return the test tube to the test tube rack.

❷ 18. Using the particulate-level representations provided in the Getting Your Brain in Gear questions as a guide, draw gas molecules in the "Final" test tube to represent the pressure change you observed.

❷ 19. Explain how the pressure data collected helped you determine what happened in Test Tube B.

    The data indicated that the final pressure was less than the initial pressure. As there was no change in volume, the decrease in pressure must have resulted from a decrease in the number of gas particles. (Temperature was not measured, so no conclusion based on any change in temperature can be made.)

20. Dispose of the unknowns in the proper waste containers. Clean the beakers and test tubes with soapy water.

Initial   Final

Initial   Final

1 min.
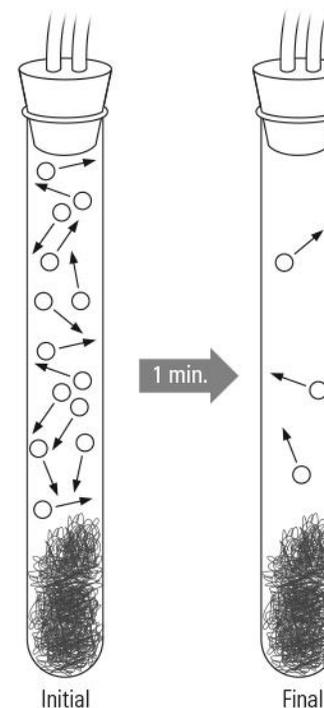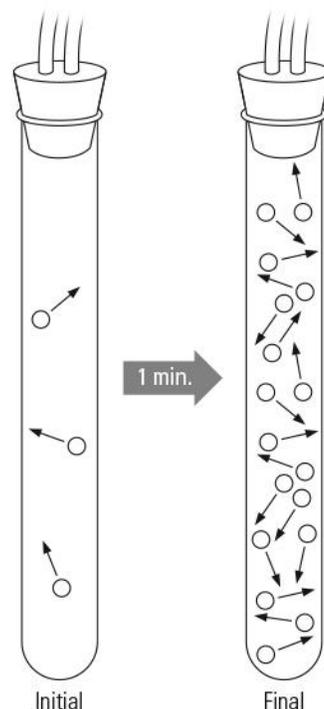
Model 2 – Chemical versus Physical Change

Table 2: Model 2 Data Table—Determining a chemical or physical change

Test Tube	Gas Visible?	Pressure Change (Increase/Decrease/Same)	Changes to Overall Appearance of Substances
A	No	Increase	No color change
B	No	Decrease	Gray metal changes to red

Analyzing Model 2 – Chemical versus Physical Change

21. One of the changes observed in Model 2 was a chemical change and the other was a physical change. Use the particulate-level representations below and your data to answer the following questions.

Test Tube A
Physical change

Test Tube B
Chemical change
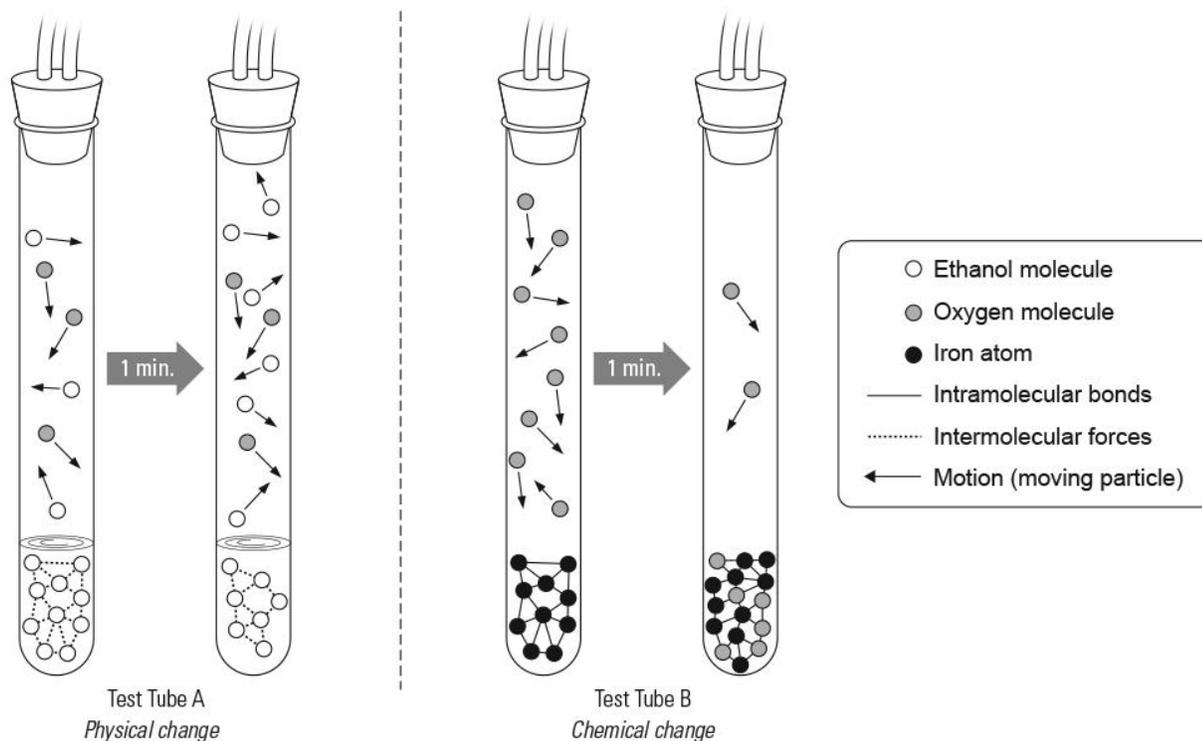
a. Label each diagram as representing either Test Tube A or Test Tube B.

b. Use the chemical change definition your group developed for Model 1 to identify which test tube, A or B, contained the chemical change. Explain why it is a chemical change.

Test Tube B contained the chemical change because new bonds were created and atoms were rearranged.

22. An increase or decrease in pressure cannot, by itself, be used to differentiate between a physical or chemical change, but it does provide insight to what is happening with the substances.

a. Explain how the pressure sensor was important in understanding what is happening inside the two different test tubes?

The gas particles are too small to see. The change in pressure displayed by the pressure sensor indicates that the number of gas molecules are increasing or decreasing.

b. What other data helped you determine if a physical or chemical change occurred in the two test tubes?

The color change of the metal in Test Tube B indicated that a new substance had formed.

23. Consider the following statements and label them as representative of a chemical or physical change.

<u>Physical</u> a. Forming or breaking intermolecular forces

<u>Chemical</u> b. Forming or breaking intramolecular forces or bonds

24. Revisit the particulate-level representations in question #5 of Getting Your Brain in Gear.

a. Which representations are chemical changes?

ii and iii

b. Which representations are physical changes?

i and iv

25. In discussing the results of the reaction in Test Tube B, a student states "The stopper must be leaking, causing a drop in pressure." Explain why a drop in pressure cannot possibly result from a leak in the stopper in this situation.

The initial pressure in the test tube was equal to the pressure outside the test tube. In order for the pressure in the test tube to drop, the "leak" would need to be from the test tube out to the surroundings. For this to occur, the pressure in the test tube would need to be higher than that outside.

26. List at least two variables in the Test Tube B reaction that could be studied to determine how they might affect the magnitude of the pressure drop during the reaction.

Variables that could be investigated: the mass of the solid unknown, the size of the test tube, the identity of the gas in the test tube, the length of time the unknown solid remained in the vinegar, the reaction time.

MODEL 3

Building Model 3 – Ambiguous changes

1. Carry out the reaction your teacher assigns your group.

❷ 2. Which change will your lab group complete?
   Answers will vary.

❷ 3. Predict what will change in terms of pH, temperature, and conductivity.
   Answers will vary. Refer to the Model 3 Data Table for the results of each pair of reactants.

❷ 4. Predict whether the change will be a chemical or physical change.
   Answers will vary. Refer to the answers in the Analyzing Model 3 section.

5. Obtain a clean and dry 100-mL beaker.

6. Start a new experiment on the data collection system.

7. Connect the pH, conductivity, and temperature sensors.

8. Set up the screen to display temperature, pH, and conductivity.

9. Pour 50 mL of distilled water into the beaker. Record the initial pH, temperature, and conductivity in the Model 3 Data Table.

10. Add a small *pea sized* sample (about 0.5 g) of the other reactant to the beaker. Stir with the stirring rod.

11. Use the sensors to measure the final pH, temperature, and conductivity of the contents of the beaker immediately after the reactants are mixed. Record these in the Model 3 Data Table.

12. When all lab groups are finished with data collection, share data to complete the Model 3 Data Table.

13. Dispose of the contents of the beakers in the proper waste containers. Clean the beakers and test tubes with soapy water. Rinse the sensors with distilled water and properly disconnect them.

Model 3 – Ambiguous changes

Table 3: Model 3 Data Table—Determining the type of change

Reactants	Observations	Condition	pH	Temp (°C)	Conductivity (Low/Med/High)
$C_{12}H_{22}O_{11}$ + H_2O	Dissolves	Initial	7	25	Low
		Final	7	25	Low
NaCl + H_2O	Dissolves	Initial	7	25	Low
		Final	7	25	High
$NaCH_3COO$ + H_2O	Dissolves	Initial	7	25	Low
		Final	8.7	30	High
Ca + H_2O	Bubbles	Initial	7	25	Low
		Final	9	35	Med/High
NH_4NO_3 + H_2O	Dissolves	Initial	7	25	Low
		Final	4	20	High

For conductivity:

Low: Less than 100 µS/cm
Med: Between 100 µS/cm and 1000 µS/cm
High: Greater than 1000 µS/cm

Analyzing Model 3 – Ambiguous changes

14. For the change that you observed, draw a particulate-level representation of the reaction that helps explain the data you collected with the sensors. Explain how the particulate-level representation is consistent with your data.

$C_{12}H_{22}O_{11}$ + H_2O / Physical

☐ = $C_{12}H_{22}O_{11}$
⊶ = H_2O

☐ = $C_{12}H_{22}O_{11}$
⊶ = H_2O

NaCl + H_2O / Ambiguous

⊕ = Na^+
⊟ = Cl^-
⊶ = H_2O

⊕ = Na^+
⊟ = Cl^-
⊶ = H_2O

$NaCH_3COO$ + H_2O / Chemical

☐◯ = $NaCH_3COO$
⊶ = H_2O

⊶ = H_2O
⊞ = Na^+
⊖ = CH_3COO^-
⊖ = OH^-
◯ = CH_3COOH
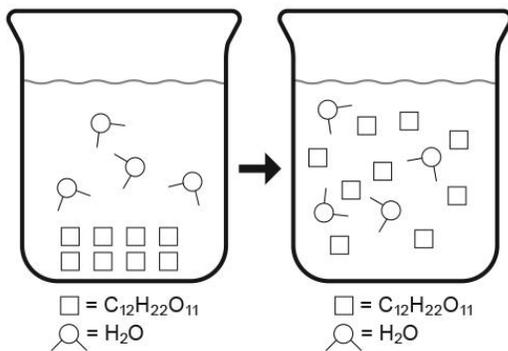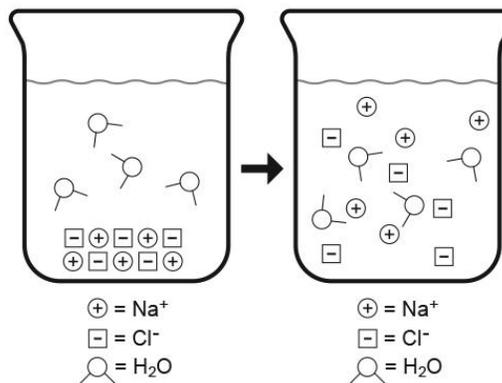
Ca + H_2O / Chemical

△ = Ca
⊶ = H_2O

△ = Ca^{2+}
⊖ = OH^-
× = H_2
⊶ = H_2O
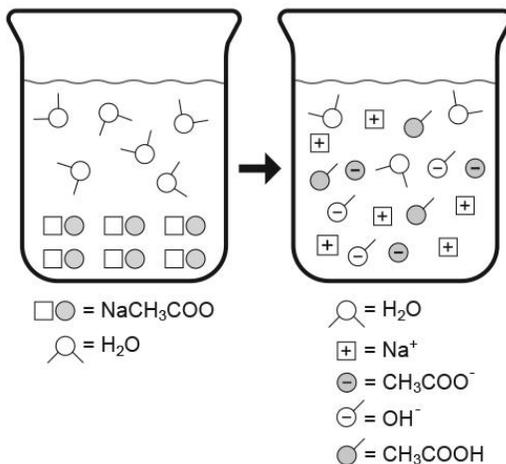
NH_4NO_3 + H_2O / Chemical

☐▷ = NH_4NO_3
⊶ = H_2O

⊕ = H_3O^+
▷ = NO_3^-
⊏ = NH_3
⊞ = NH_4^+
⊶ = H_2O
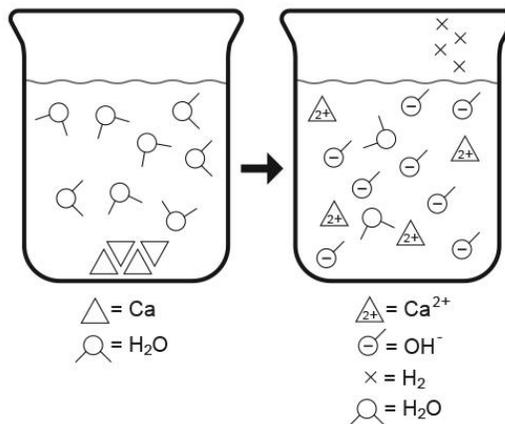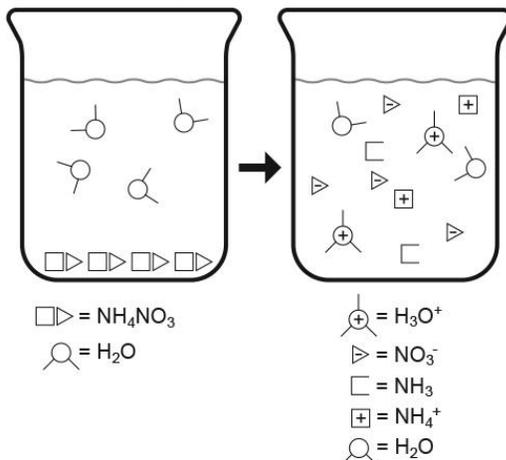
- $C_{12}H_{22}O_{11}$ + H_2O – There was no measurable change in conductivity (which was low), pH (which was neutral), or temperature, so there aren't any ions formed. The sugar molecules simply dissolve, as shown.
- $NaCl$ + H_2O – The solid dissolved and the conductivity increased, as represented by the ions shown in the solution.
- $NaCH_3COO$ + H_2O – The increase in pH means water lost an H^+ ion, making a greater concentration of OH^- ions in the solution. The increase in conductivity also means there are more ions in solution, as shown in the representation.
- Ca + H_2O – The increase in pH means water lost an H^+ ion, leaving OH^- ions in solution. The bubbles indicate the production of a gas, most likely hydrogen, which implies intramolecular changes occurred. Also, the increase in conductivity means more ions were present in the solution and the increase in temperature indicates the formation of bonds to make H_2.
- NH_4NO_3 + H_2O – The decrease in pH means water gained an H^+ ion, making H_3O^+ ions in solution. Also, the increase in conductivity means more ions are in solution. The decrease in temperature indicates bonds are broken.

15. Determine if each change is a chemical, physical, or ambiguous change. Support your answer with evidence from Model 3. Specify whether intramolecular or intermolecular bonds were affected. Was your prediction correct?

- $C_{12}H_{22}O_{11}$ + H_2O – Physical change. There was no visible change or change in sensor measurements. Intermolecular bonds are affected.
- $NaCl$ + H_2O – Ambiguous change. The solid dissolved and there was an increase in conductivity, but neither the pH nor the temperature changed, so it is not clear if this is a physical or chemical change. Intramolecular bonds are affected.
- $NaCH_3COO$ + H_2O – Chemical change. There was no visible change, but the increase in temperature, increase in conductivity, and increase in pH indicate a chemical change. Intramolecular bonds are affected.
- Ca + H_2O – Chemical change. Visible changes (bubbling) and the increase in temperature, conductivity, and pH indicate a chemical change occurred. Intramolecular bonds are affected.
- NH_4NO_3 + H_2O – Chemical change. There was no visible change, but the decrease in temperature, increase in conductivity, and decrease in pH indicate a chemical change occurred. Intramolecular bonds are affected.

16. Two students were having a disagreement about whether $NaNO_3$ mixed with water results in a physical or chemical change. Student A claims it is a physical change because no new substance is formed and upon evaporation of the water, $NaNO_3$ could be recovered since only intermolecular forces change during dissolution. Student B claims it is a chemical change because the ionic bonds in $NaNO_3$, which are intramolecular, are broken by the water. This forms new ions, Na^+ and NO_3^-, that affect conductivity. What would your group tell Students A and B?

Answers will vary. This change is ambiguous.

Connecting to Theory

When a process is classified as a chemical change, intramolecular interactions change, producing a new, chemically distinct substance due to the rearrangement of atoms. When a process is classified as a physical change, intermolecular interactions change. No new substances are produced. Atoms within the original molecules do not rearrange. Some processes can be labeled ambiguous changes when both intramolecular and intermolecular interactions change during the process.

Applying Your Knowledge

1. Reflecting on the entire lab, is identifying an unknown change as physical or chemical straightforward? Write a paragraph explaining your thoughts using data collected from this lab.

   Answers will vary. Most students will say it is not straightforward, as parts of the Model 3 activity illustrate several changes that appear to be physical when you observe the reaction but show changes in temperature or conductivity that would indicate otherwise.

2. Scientific sensors can be used to understand what is happening on a scale far too small for humans to directly observe. Reflect on your use of technology during this lab. Write a paragraph on how technology can be used to visualize processes that cannot be directly observed. Use external resources to find examples of sensors not used in this lab.

   Answers will vary. Students may write how technology allows them to have some insight into what is occurring at the molecular level and that it enables scientists to collect large amounts of data accurately and to display, analyze, and interpret their data more quickly. For this lab, technology provided insight into molecular level activity—the temperature sensor, conductivity sensor, and pH sensor indicated changes within intramolecular bonds, the formation or reaction of ions, and the presence of acids and bases, respectively.

   Other measurement sensors include gas monitoring sensors (for example, carbon dioxide and oxygen gas sensors), spectrometers and colorimeters, and voltage sensors.

Teacher Tips

Tip 1 – Other options for Unknown 2A

Instead of ethanol, use a small piece of dry ice (CO_2).

Tip 2 – Lead a class discussion of the Getting Your Brain in Gear answers before starting the lab

To ensure success in the lab, make sure students understand the particulate-level diagrams, especially with pH and hydronium ions, as well as the terms "intermolecular" and "intramolecular."

Tip 3 – Confirm data accuracy of all Models before lab groups answer questions

Answers to the Analyzing Model questions are dependent on accurate data. Confirm the accuracy of data to ensure that students will construct accurate knowledge. When using acids and bases especially, any impurity in or on the beaker could change the pH reading drastically. Make sure the students thoroughly rinse all beakers and graduated cylinders before adding the unknown solutions.

2. LIGHT, COLOR, AND CONCENTRATION

Initial Question

If you've ever added a powdered drink mix to water, you realize that the more concentrated the drink, the deeper the color of the solution. Analytical chemists, particularly in the agricultural and medical fields, routinely use a quantitative approach called *spectroscopy* to determine the concentration of solute in a solution as it relates to the color of the solution.

How can you use electromagnetic waves to determine the concentration of a solution?

Learning Objectives[*]

Students learn how to use visible light to determine the concentration of colored ion species in a solution.

LO 1.16 / The student can design and/or interpret the results of an experiment regarding the absorption of light to determine the concentration of an absorbing species in a solution.

SP 4.1 / The student can *justify the selection of the kind of data* needed to answer a particular scientific question.

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

SP 4.3 / The student can *collect data* to answer a particular scientific question.

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

SP 5.3 / The student can *evaluate the evidence provided by data sets* in relation to a particular scientific question.

Time Requirements

Preparation time: 20 minutes / Lab activity: 90 minutes

Materials and Equipment

Model 1

- Data collection system
- Colorimeter
- Cuvette[1]
- Sensor extension cable[1]
- Pipet with pump or bulb, 10-mL
- White 3 × 5 index card or piece of paper
- Colored pencils
- Scissors

- Distilled water and wash bottle
- Kimwipes or tissues
- One of the following:
  0.10 M Cobalt(II) nitrate ($Co(NO_3)_2$), 30 mL[2]
  0.10 M Nickel(II) nitrate ($Ni(NO_3)_2$), 30 mL[2]
  0.10 M Iron(III) nitrate ($Fe(NO_3)_3$), 30 mL[2]
  0.10 M Zinc nitrate ($Zn(NO_3)_2$), 30 mL[2]

[1]Included with PASCO Colorimeter.
[2]To formulate these solutions, refer to the Lab Preparation section.

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Model 2

- Data collection system
- Colorimeter
- Cuvette[1]
- Sensor extension cable[1]
- Distilled water and wash bottle
- Test tubes (5), large
- Test tube rack
- Pipet with pump or bulb, 10-mL

- Glass stirring rod
- Kimwipes or tissues
- One of the following:

  0.10 M Cobalt(II) nitrate ($Co(NO_3)_2$), 30 mL[2]

  0.10 M Nickel(II) nitrate ($Ni(NO_3)_2$), 30 mL[2]

  0.10 M Iron(III) nitrate ($Fe(NO_3)_3$), 30 mL[2]

  0.10 M Copper(II) sulfate ($CuSO_4$), 30 mL[2]

[1]Included with PASCO Colorimeter.

[2]To formulate these solutions, refer to the Lab Preparation section.

Applying Your Knowledge

- Data collection system
- Colorimeter
- Sensor extension cable[1]
- Cuvette[1]
- Pipet with pump or bulb, 10-mL

- Distilled water and wash bottle
- Kimwipes or tissues
- 0.10 M Copper(II) nitrate ($Cu(NO_3)_2$), 30 mL[2]
- Copper(II) nitrate ($Cu(NO_3)_2$), unknown concentration, 6 mL[2]

[1]Included with PASCO Colorimeter.

[2]To formulate these solutions, refer to the Lab Preparation section.

Prerequisites

Students should be familiar with the following concepts:

- Electromagnetic spectrum

- Molarity

- Interaction of light energy with electrons

Lab Preparation

These are the materials and equipment to set up prior to the lab:

NOTE: For Models 1 and 2, assign a different solution to each group so all solutions are analyzed. Students share data for the solutions they haven't analyzed.

Model 1 and Model 2

1. **0.1M Cobalt(II) nitrate:** Prepare 250 mL of a 0.1 M solution of cobalt(II) nitrate by adding 7.28 g of solid $Co(NO_3)_2 \cdot 6H_2O$ to a 250 mL volumetric flask and fill to the mark with distilled water.

2. **0.1M Nickel(II) nitrate:** Prepare 250 mL of a 0.1 M nickel(II) nitrate by adding 7.27 g of solid $Ni(NO_3)_2 \cdot 6H_2O$ to a 250 mL volumetric flask and fill to the mark with distilled water.

3. **0.1M Iron(III) nitrate:** Prepare 250 mL of a 0.1 M iron(III) nitrate by adding 10.10 g of $Fe(NO_3)_3 \cdot 9H_2O$ to a 250 mL volumetric flask and fill to the mark with distilled water.

4. **0.1M Zinc nitrate:** Prepare 250 mL of 0.10 M zinc nitrate by adding 7.43 g of solid $Zn(NO_3)_2 \cdot 6H_2O$ to a 250 mL volumetric flask and fill to the mark with distilled water.

   NOTE: This solution is only used in Model 1.

Model 2

5. **0.1M Copper(II) sulfate:** Prepare 250 mL of 0.10 M copper(II) sulfate by adding 6.24 g of solid $CuSO_4 \cdot 5H_2O$ to a 250 mL volumetric flask and fill to the mark with distilled water.

    NOTE: Give this solution to the groups that analyzed zinc nitrate in Model 1.

Applying Your Knowledge

6. **0.1M Cobalt(II) nitrate:** Prepare 250 mL of 0.10 M copper(II) nitrate by adding 6.04 g of solid $Cu(NO_3)_2 \cdot 3H_2O$ to a 250 mL volumetric flask and fill to the mark with distilled water.

7. **Unknown Cobalt(II) nitrate:** Prepare 250 mL of unknown copper(II) nitrate by adding between 3.0 and 5.0 g of solid $Cu(NO_3)_2 \cdot 3H_2O$ to a 250 mL volumetric flask and fill to the mark with distilled water. Make several solutions of different concentrations, calculating the concentration for each, and keep track of which groups get which unknown.

Safety

Add these important safety precautions to your normal laboratory procedures:

- Wash your hands with soap and water after handling the solutions, glassware, and equipment.

- Nickel(II) nitrate, cobalt(II) nitrate, iron(III) nitrate, zinc nitrate and copper(II) sulfate are hazardous to the environment and should not be disposed of down the drain. Make sure you follow your teacher's instructions on how to properly dispose of these solutions.

Getting Your Brain in Gear

1. Which color of light has the higher energy—blue or red?

    Blue

2. The atomic theory put forth by Bohr was based on the interaction of light with electrons at various energy levels. According to Bohr's theory, what could happen to an electron that was hit by a photon of light?

    If the photon has the correct energy, the electron would move to a higher energy level orbit.

3. According to Bohr's theory, what must happen for an excited electron to move to a lower energy state?

    The electron must lose energy. This might be done by emitting a photon of light.

4. According to Bohr's theory, how is the change in the electron's energy different if it absorbs the energy of red light versus absorbing the energy of blue light?

    An electron that absorbs the energy from blue light could move to a much higher energy level than a similar electron that absorbs the energy from red light.

5. White light passed through a prism comes out as a rainbow. Describe white light in terms of a mixture of photons.

    White light is a mixture of photons with various energies. There are several different "red" energy photons, "orange" energy photons, "green" energy photons and so on.

MODEL 1

Building Model 1 – Transmittance and Absorbance for Solutions

1. Start a new experiment on the data collection system.

2. Connect the colorimeter to the data collection system using the extension cable.

3. Place a 1 cm × 7 cm piece of white paper in the sample cell compartment of the colorimeter.

4. Press the green button and observe the light as it appears on the paper. You may need to shade the cell compartment from room light with your hand.

❷ 5. What colors of light appear on the paper (list at least three)?

   Red, orange (hard to see), green, and blue.

6. Record the color of light emitted by the colorimeter above their corresponding wavelengths in the Model 1 Data Table.

7. Obtain a sample of a 0.10 M solution to test in the colorimeter for Model 1. Your instructor will assign you either cobalt(II) nitrate, nickel(II) nitrate, iron(III) nitrate or zinc nitrate.

8. Record the color of your solution in the Model 1 Data Table.

9. Fill a cuvette at least ¾ full with distilled water.

10. Wipe off the sides of the cuvette and only handle it by the top.

11. Calibrate the colorimeter with the distilled water (the water sample is called a "blank").
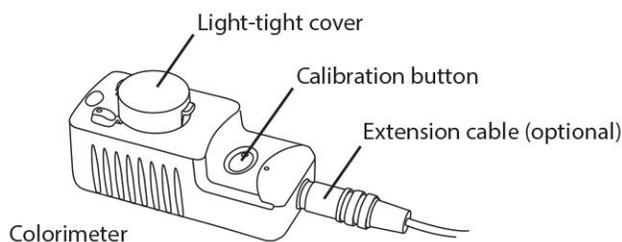
❷ 12. Why is it important to wipe off the sides of the cuvette before placing it into the colorimeter?

   Any material on the outside of the cuvette will decrease the amount of light that can reach the sample.

❷ 13. What is the approximate percent transmittance at each of the four wavelengths?

   100%

❷ 14. What is the approximate absorbance at each of the four wavelengths?

   0

❷ 15. The solutions you are about to test in the colorimeter are aqueous solutions. That is, water is the solvent. Both water and glass can absorb visible light at some wavelengths. With this in mind, explain why the colorimeter is calibrated with a blank solution? (Hint: Using a "blank" in a colorimeter is similar to the "tare" button on a digital balance.)

   The blank solution makes sure that the readings on the colorimeter are from the solute in the test solutions only, and not from the distilled water solvent.

16. Place ~6 mL of your assigned 0.10 M test solution into the cuvette. Wipe the cuvette and handle it only from the top.

17. Place the cuvette in the colorimeter chamber and close the cover. Record your transmittance and absorbance data in the Model 1 Data Table for each of the four wavelengths.

18. Share your data with other groups to complete Table 1.

Model 1 – Transmittance and Absorbance for Solutions

Table 1: Model 1 Data Table—Light transmittance and absorbance for solutions of different colors

0.1 M Solution	Red		Green		Blue		Orange	
	660 nm		565 nm		468 nm		610 nm	
	%T	A	%T	A	%T	A	%T	A
$Co(NO_3)_2$ Color: _____red_____	90.6	0.043	71.7	0.145	43.7	0.358	87.0	0.061
$Ni(NO_3)_2$ Color: _____green_____	57.0	0.244	89.7	0.048	100.0	0.000	77.8	0.109
$Fe(NO_3)_3$ Color: _____orange_____	94.2	0.026	87.5	0.058	12.8	0.891	94.5	0.025
$Zn(NO_3)_2$ Color: _____colorless_____	100.0	0.000	100.0	0.000	100.0	0.000	100.0	0.000

Analyzing Model 1

19. Consider the words "transmit" and "absorb" as they are used normally.

    a) If a solution has a high transmittance for a certain color of light, what does that mean in terms of photons of light interacting with electrons in the solution?

    It means the photons of light move through the solution and do not interact with the electrons in the solute.

    b) When a solution has a high transmittance for a certain color of light, does it also have a high absorbance for that color? Use specific evidence from Model 1 to justify your answer.

    No. High transmittance values correspond with low absorbance values. The highest transmittance values for cobalt(II) nitrate are for wavelengths 660 and 610. These wavelengths gave the lowest absorbance values for that solution: 0.043 and 0.061.

    c) Explain the relationship you stated above in terms of the interaction of photons of light with electrons in the solution.

    If a photon with a certain wavelength is transmitted through the solution, it is NOT absorbed. Therefore a high transmittance would correspond to a low absorption.

20. All of the solutions used in Model 1 were made by dissolving a salt in distilled water. For each solution, list the individual ions present after the salt has completely dissolved.

$$\text{Cobalt(II) nitrate} \quad = \quad Co^{2+} \text{ and } NO_3^{1-}$$
$$\text{Nickel(II) nitrate} \quad = \quad Ni^{2+} \text{ and } NO_3^{1-}$$
$$\text{Iron(III) nitrate} \quad = \quad Fe^{3+} \text{ and } NO_3^{1-}$$
$$\text{Zinc nitrate} \quad = \quad Zn^{2+} \text{ and } NO_3^{1-}$$
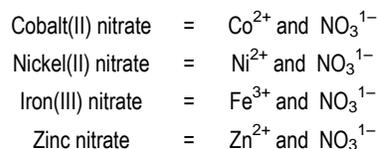
21. Identify the ions that cause the solutions to have color.

    Co^{2+}, Ni^{2+}, Fe^{3+}
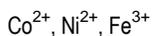
22. Use colored pencils to color the beakers below containing the solutions from Model 1. Assemble the accessory photogate near the edge of the lab table. Point out related information. Point out related information.

Key

—————	all transmitted
– – – – –	a lot transmitted
··············	some transmitted
	none transmitted
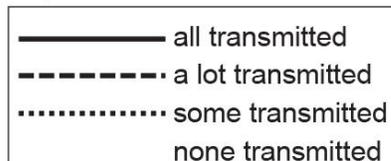
Example

If all lights (red, orange, green, and blue) came from the instrument fully and were transmitted fully through the solution, it would be illustrated like this:
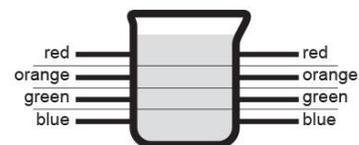
23. In the diagrams above use solid or dotted lines of the appropriate color to represent both the incoming light and the outgoing light for each of the four wavelengths as they traveled through each solution. The diagrams should be consistent with the data collected in Model 1.

24. State the formula and color of the solution which absorbed the most

    a) green light

       $Co(NO_3)_2$; red solution

    b) blue light

       $Fe(NO_3)_3$; orange solution

    c) red light

       $Ni(NO_3)_2$; green solution

25. Consider the solutions in Model 1. When light is shone through a solution that matches the color of the solution, is it mostly transmitted or absorbed? Justify your answer with data from Model 1.

    Light that matches the color of the solution is mostly transmitted. Iron(III) nitrate is an orange solution. When orange light shone on this solution there was a high transmittance (94.5%).

26. Consider the color wheel below. Red and green are considered complementary colors, as are violet and yellow. When light is shone through a solution that is a complementary color to that of the solution, is it mostly transmitted or absorbed? Justify your answer with data from Model 1.
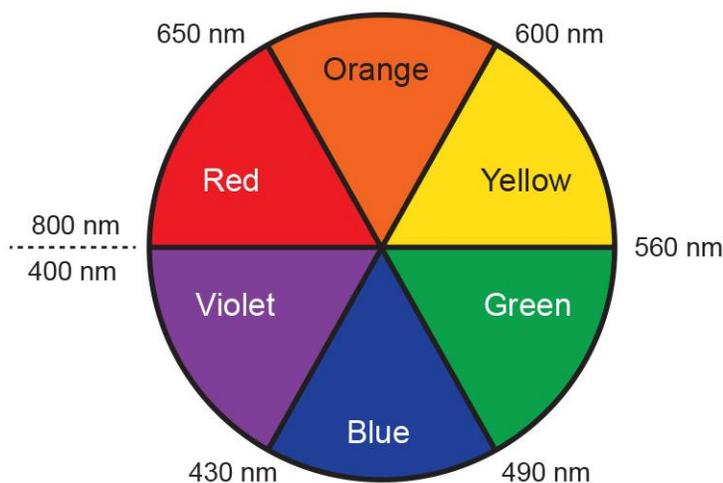
    Light that is a complementary color to the solution's color is mostly absorbed. Nickel(II) nitrate is a green solution, and when red light shone on this solution there was a high absorbance of 0.244.

27. Can wavelengths of visible light be used to analyze the concentration of colorless solutions? Justify your answer with evidence from Model 1.

    No. The zinc solution was colorless and it did not absorb any of the wavelengths of visible light.

Connecting to Theory

When we look at something white, our eyes are picking up light of every wavelength that is reflecting off of that object. Colored objects absorb one or more wavelengths of light, however, so our eyes only receive part of the visible spectrum. Thus our brain registers the object as having a color. A red object, for example, might absorb blue, yellow and green wavelengths. Our brain receives the reflected violet, red and orange wavelengths and "averages" them together, making us think we have seen red.

MODEL 2

Building Model 2 – Varying Concentration

1. Label five clean, dry test tubes "1" through "5" and place them into a test tube rack.

2. Pipet 2.0, 4.0, 6.0, 8.0 and 10.0 mL of your assigned colored 0.10 M solution into test tubes 1 through 5, respectively. (If you previously used a colorless solution, ask your instructor which colored solution you should use for Model 2.)

3. Wash the pipet and use it to deliver 8.0, 6.0, 4.0, and 2.0 mL of distilled water into test tubes 1 through 4 so that each test tube has 10.0 mL of solution.
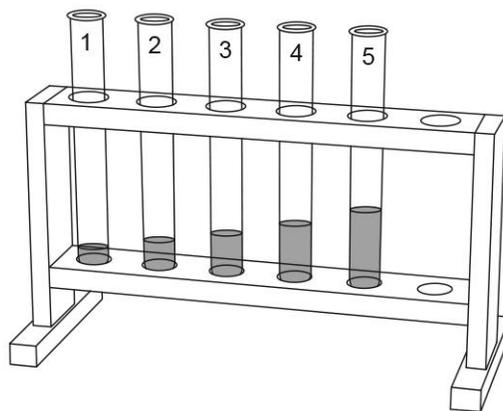
❷ 4. Why do the test tubes need to be dry? What error would be caused by wet test tubes?

Wet test tubes would change the molarity of the standards, making our calibration graph incorrect.

❷ 5. Calculate the concentration of the solutions in each test tube, and enter those values in the Model 2 Data Table.

The undiluted solution was 0.10 M. Final concentration = ($V_{\text{Colored solution}}$ × 0.1 M) / V_{Final}

For the first test tube: (0.002 L × 0.1 M) / 0.010 L = 0.02 M

6. Thoroughly mix each solution with a stirring rod.

NOTE: Clean and dry the stirring rod before stirring a different solution.

7. Configure the data collection system to manually collect the absorbance and transmittance data of all four wavelengths and the solution concentration in a table. Define the concentration as a manually entered data set with units of molarity.

8. Begin with the solution with the lowest concentration. Rinse the cuvette twice with a small portion of the solution and then fill the cuvette two-thirds full.

9. Wipe the cuvette clean and dry and place it into the colorimeter

10. Record the absorbance and transmittance in the Model 2 Data Table for each of the four wavelengths of light.

11. Rinse the cuvette and record data for each of the other four solutions of known concentration.

Model 2 – Varying Concentration

Solution: _____ $CuSO_4$ _____

Table 2: Model 2 Data Table—Detecting the concentration of a solution using light

Test Tube #	Concentration (M)	Red (660 nm)		Green (565 nm)		Blue (468 nm)		Orange (610 nm)	
		%T	A	%T	A	%T	A	%T	A
1	0.02 M	78.4	0.106	98.3	0.007	100.0	0.000	93.3	0.030
2	0.04 M	61.1	0.213	94.6	0.025	100.0	0.000	86.4	0.064
3	0.06 M	49.2	0.308	90.7	0.043	100.0	0.000	79.5	0.100
4	0.08 M	40.3	0.395	89.8	0.047	100.0	0.000	74.7	0.127
5	0.10 M	31.9	0.496	87.1	0.060	100.0	0.000	69.9	0.157

Analyzing Model 2 – Varying Concentration

12. Graph the four sets of absorbance versus concentration data for your solution. Use color pencil (or colored lines) to indicate the wavelength of light used to collect each set of data.

Absorbance versus Concentration of $CuSO_4$

$y = 4.810x + 0.015$

$y = 1.585x + 0.000$

$y = 0.640x - 0.002$

$y = 0.000$

Red (660 nm)

Orange (610 nm)

Green (565 nm)

Blue (468 nm)

13. Which color of light provides absorbance data with the steepest slope? Which color of light gives data with the shallowest slope?

    Answers will vary depending on which solution students investigated. Refer to Table 3 for expected results.

14. Check with lab groups that tested different colored solutions. Record their answers to the question above regarding the color of light that provides the steepest slope in Table 3.

Table 3: Wavelength displaying the greatest change in absorbance as concentration changes

Parameter	Group Results for:			
	Cobalt(II) nitrate	Nickel(II) nitrate	Iron(III) nitrate	Copper(II) sulfate
Color of solution	Red/blue	Green	Orange/yellow	Blue
Color of light with steepest slope	Green	Red	Blue/green	Red
Color of light with shallowest slope	Red	Green	Orange	Blue

15. In general, is the absorbance data with the steepest slope obtained from light that matches the color of the solution or from the complementary color?

    A complementary color of light provides data with the steepest slope.

16. Imagine that your instructor gives you a sample of your solution of unknown concentration.

    a. Explain how your absorbance data might be used to find the concentration of that solution.

       Compare the absorbance of the unknown to the graph of absorbance values from the solutions of known concentration. Find the concentration that corresponds with the unknown's absorbance either by writing an equation for the line or extrapolating from the graph.

    b. Would it be best to use the wavelength of light that gave the steepest slope or the shallowest slope in determining the concentration of your unknown? Explain your reasoning.

       The data with the steepest slope will give the most precise concentration for the unknown. If the data is shallow, then a large range of concentration values will give almost the same absorbance value.

17. Graph the percent transmittance data that corresponds to the absorbance data with the steepest slope. Which set of data, $\%T$ or A, would be the easiest to model with a mathematical equation? Justify your answer.

Transmittance versus Concentration of $CuSO_4$

$y = 96.565e^{-11.07x}$

Red (660 nm)
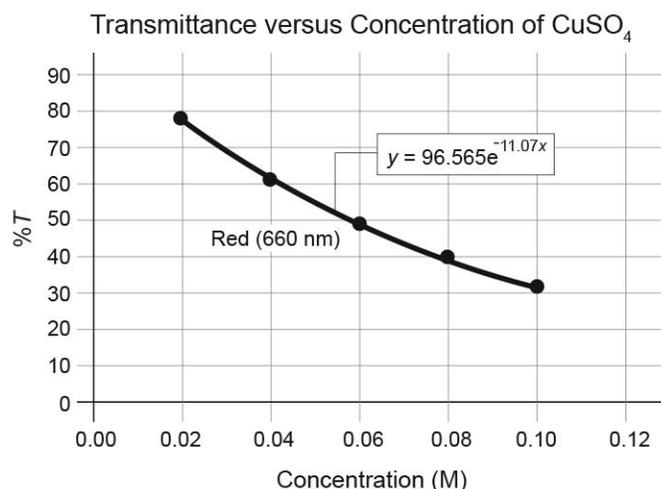
Absorbance data gives a linear line. The percent transmittance data gives a curved line. Absorbance would be much easier to model with a mathematical equation.

18. Consider the data below collected by two different lab groups for copper(II) nitrate solution at 468 nm on the same colorimeter. (Assume the spectrometer was working properly in both cases.)

Transmittance versus Concentration
of $Cu(NO_3)_2$ for two lab groups
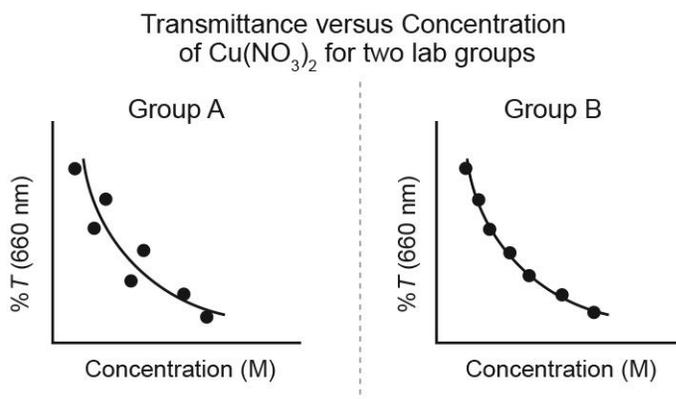
a) Discuss how the quality of the data compares between the two groups.

Group A's data does not fit the linear model as tightly. Their data is not as precise. Group B's data is more precise because it fits the linear model better.

b) Propose at least two reasons why the data might differ between the two groups.

Group A students may not have stirred their diluted solutions when they prepared them.

Group A students may not have wiped the cuvettes before placing them in the colorimeter.

Connecting to Theory

Spectroscopy is the study of the interaction of electromagnetic radiation and matter. In spectroscopy and spectrophotometry, two terms are inescapable: transmittance and absorbance. Transmittance T is defined as the ratio of the intensity of light after it passes through a medium being studied (I) to the intensity of light before it encounters the medium (I_0).

$$T = \frac{I}{I_0}$$

Chemists more commonly refer to the percent transmittance %T, which is simply $\frac{I}{I_0} \times 100$. Because the percent transmittance is exponentially related to concentration of solute, the use of absorbance, which gives a linear relationship, is often preferred.

$$A = -\log T = -\log \frac{I}{I_0} \quad ; \text{note that } A = -2 \log (\%T)$$

If one knows the percent transmittance, one can calculate absorbance and vice versa. Most modern spectrophotometers have both a %T and an absorbance scale. With a digital instrument, it is simply a matter of changing modes to display either value.

Beer's Law, is one of the most fundamental and widely applied spectroscopic laws. It relates the absorbance of light to the concentration c of the solute, the optical path length b and the molar absorptivity a of a solution.

An operation statement of Beer's Law can be represented as

$$A = abc$$

The molar absorptivity is a constant that depends on the nature of the absorbing solution system and the wavelength of the light passing through it. A plot that shows the dependence of A on wavelength is called a spectrum.

Applying Your Knowledge– Determining the Concentration of an Unknown

Your instructor will provide you with a bottle of 0.10 M copper(II) nitrate and a sample of an unknown concentration of copper(II) nitrate. Propose and carry out a plan to determine the concentration of the copper ion in the unknown. What is the concentration of the unknown?

Plan:

1. Make several dilutions of the 0.10 $Cu(NO_3)_2$: 0.02 M, 0.04 M, 0.06 M, 0.08 M, and record their absorbance and transmittance.

2. Display a graph of the absorbance versus molarity data, since that results in a linear line, and obtain the slope of the line of the absorbance,

3. Record the absorbance and transmittance of the unknown.

4. Use the slope of the line to calculate the unknown concentration.

Using colorimetric data to determine a sample's concentration

Concentration	Red (660 nm)		Green (565 nm)		Blue (468 nm)		Orange (610 nm)	
(M)	A	%T	A	%T	A	%T	A	%T
0.02	0.104	78.7	0.016	92.6	0.000	100.0	0.034	92.5
0.04	0.192	64.4	0.026	94.2	0.000	100.0	0.057	87.7
0.06	0.290	51.2	0.044	90.3	0.000	100.0	0.092	81.0
0.08	0.369	42.7	0.053	88.4	0.000	100.0	0.123	75.3
0.10	0.477	33.3	0.065	86.2	0.000	100.0	0.149	71.0
Unknown	0.307	49.4	0.045	90.2	0.000	100.0	0.098	79.8

Absorbance versus Concentration of $Cu(NO_3)_2$
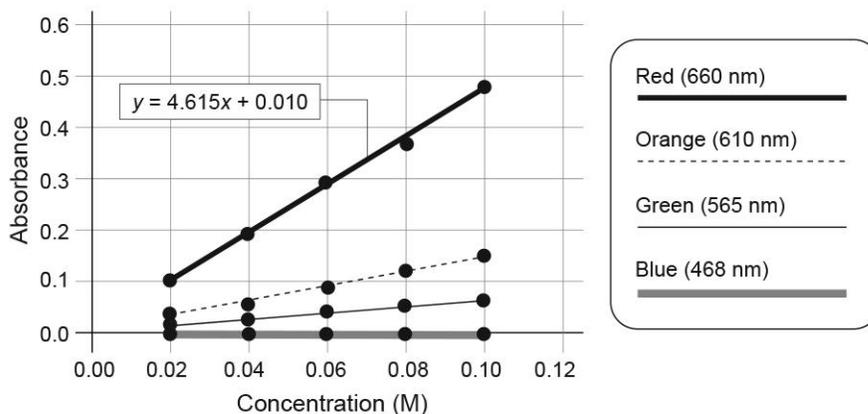
$y = 4.615x + 0.010$

Using the slope of the line to calculate the unknown concentration:

$y = 4.615x + 0.0095$

$0.307 = 4.615x + 0.0095$

$x = 0.07$ M

The concentration is 0.07 M $Cu(NO_3)_2$.

Teacher Tips

Tip 1 – Pre-lab Demo

This demonstration may be helpful for students before this lab is performed: Use a small beaker containing water and red food coloring to show that the light from a red laser pointer will go right through the solution, but the light from a green laser pointer will not. This provides an opportunity to introduce the terms absorption and transmittance.

Tip 2 – Path Length and Cuvettes

Illustrate to students the importance of using a standard sized container for spectrophotometric experiments. Pour a colored solution into a beaker and a test tube. Observe the colors. Note the solution in the beaker appears darker even though it is the same concentration. Discuss path length with students, and note that the use of cuvettes keeps this variable constant during the experiment.

3. GRAVIMETRIC ANALYSIS OF A PRECIPITATE

Initial Question

Chemists can find the identity of unknown compounds using techniques such as qualitative analysis, chromatography, spectroscopy, and gravimetric analysis. Gravimetric analysis, which uses a balance to determine the mass of a substance, is one of the oldest and most accurate quantitative methods for determining the amount of an analyte in a sample.

Can you determine the amount and identity of an unknown component of a substance?

Learning Objectives[*]

Through gravimetric analysis, students identify an unknown alkali metal carbonate.

LO 1.3 The student is able to select and apply mathematical relationships to mass data in order to justify a claim regarding the identity and/or estimated purity of a substance.

LO 1.19 The student can design, and/or interpret data from, an experiment that uses gravimetric analysis to determine the concentration of an analyte in a solution.

SP 4.3 The student can *collect data* to answer a particular scientific question.

SP 5.3 The student can *evaluate the evidence provided by data sets* in relation to a particular scientific question.

SP 6.1 The student can *justify claims with evidence*.

Time Requirement

Day 1: Preparation time: 20 minutes / Lab activity: 40 minutes

Day 2: Lab activity: 40 minutes

Day 3: Lab activity: 10 minutes

Materials and Equipment

Model 1

- Beakers (4), glass, 100-mL
- Beral pipets (4)
- Unknown A (alkali metal carbonate), 5.0 g[1]
- 0.10 M Sodium nitrate, ($NaNO_3$), 5 drops[2]
- 0.10 M Potassium chloride, (KCl), 5 drops[2]
- 0.10 M Ammonium nitrate, (NH_4NO_3), 5 drops[2]
- 0.10 M Calcium chloride, ($CaCl_2$), 5 drops[2]
- Stirring rod
- Marking pen (to label beakers)
- Distilled water, 200 mL

[1]Unknown A is K_2CO_3.
[2]To prepare the solutions, refer to the Lab Preparation section.

Model 2 and Applying Your Knowledge

- Beaker, glass, 100-mL
- Filtration funnel
- Erlenmeyer flask, glass, 250-mL
- Filter paper, Whatman® Ashless, #42
- Watch glass, 100-mm

- Analytical balance, 0.001 g precision, 1 per class
- Stirring rod
- Pencil
- Wash bottle with distilled water
- Drying oven, 1 per class

Model 2

- Unknown A (same unknown as Model 1), 1.00 g[1]
- 0.25 M Calcium chloride ($CaCl_2$), 50 mL[2]

- Distilled water, 100 mL

[1] Unknown A is K_2CO_3
[2] To prepare the solution, refer to the Lab Preparation section.

Applying Your Knowledge

- Unknown B, 2.00 g[1]
- 0.50 M Potassium nitrate (KNO_3), 20 mL[2]
- 0.50 M Lithium chloride (LiCl), 20 mL[2]

- 0.50 M Calcium nitrate ($Ca(NO_3)_2$), 20 mL[2]
- 0.50 M Sodium chloride (NaCl), 20 mL[2]
- Distilled water, as needed

[1] Unknown A is Li_2CO_3
[2] To prepare the solutions, refer to the Lab Preparation section.

Prerequisites

Students should be familiar with the following concepts:

- Stoichiometry of chemical reactions
- Solubility
- Solubility Rules
- Reactions of anions and cations and the presence of spectator ions
- Using the analytical balance
- Molarity

Lab Preparation

These are the materials and equipment to set up prior to the lab:

Model 1 and Model 2

1. Use K_2CO_3 as Unknown A.

Model 1

2. **0.10 M Sodium nitrate:** To prepare 100 mL of 0.10 M sodium nitrate ($NaNO_3$), fill a 100-mL volumetric flask 1/3 full of distilled water. Add 0.850 g of sodium nitrate to the flask and swirl to dissolve. Fill to the mark with distilled water.

3. **0.10 M Ammonium nitrate:** To prepare 100 mL of 0.10 M ammonium nitrate (NH_4NO_3), fill a 100-mL volumetric flask 1/3 full of distilled water. Add 0.801 g of ammonium nitrate to the flask and swirl to dissolve. Fill to the mark with distilled water.

4. **0.10 M Calcium chloride:** To prepare 100 mL of 0.10 M calcium chloride ($CaCl_2$), fill a 100-mL volumetric flask 1/3 full of distilled water. Add 1.110 g of calcium chloride to the flask and swirl to dissolve. Fill to the mark with distilled water.

5. **0.10 M Potassium chloride:** To prepare 100 mL of 0.10 M potassium chloride (KCl), fill a 100-mL volumetric flask 1/3 full of distilled water. Add 0.746 g of potassium chloride to the flask and swirl to dissolve. Fill to the mark with distilled water.

Model 2

6. **0.25 M Calcium chloride:** To prepare 1000 mL of 0.25 M calcium chloride ($CaCl_2$), fill a 1000-mL volumetric flask 1/3 full of distilled water. Add 27.746 g of calcium chloride anhydride to the flask and swirl to dissolve. Fill to the mark with distilled water.

Applying Your Knowledge

7. Use Li_2CO_3 as Unknown B.

8. **0.50 M Potassium nitrate:** To prepare 1000 mL of 0.50 M potassium nitrate (KNO_3), fill a 1000-mL volumetric flask 1/3 full of distilled water. Add 50.552 g of potassium nitrate to the flask and swirl to dissolve. Fill to the mark with distilled water.

9. **0.50 M Lithium chloride:** To prepare 1000 mL of 0.50 M lithium chloride (LiCl), fill a 1000-mL volumetric flask 1/3 full of distilled water. Add 21.197 g of lithium chloride to the flask and swirl to dissolve. Fill to the mark with distilled water.

10. **0.50 M Calcium nitrate:** To prepare 1000 mL of 0.50 M calcium nitrate ($Ca(NO_3)_2$), fill a 1000-mL volumetric flask 1/3 full of distilled water. Add 82.044 g of calcium nitrate to the flask and swirl to dissolve. Fill to the mark with distilled water.

11. **0.50 M Sodium chloride:** To prepare 1000 mL of 0.50 M sodium chloride (NaCl) fill a 1000-mL volumetric flask 1/3 full of distilled water. Add 29.221 g of sodium chloride to the flask and swirl to dissolve. Fill to the mark with distilled water.

Safety

Add these important safety precautions to your normal laboratory procedures:

- Wear your goggles.

Getting Your Brain in Gear

1. In this lab you will be given an unknown alkali metal carbonate. Your lab group will have to determine the identity of that compound through gravimetric analysis. The unknown could be: lithium carbonate, sodium carbonate, potassium carbonate, or cesium carbonate.

   a. Does each of these compounds have the same ratio of metal atoms to carbonate ions? Explain your answer.

   Yes, they are all alkali metal carbonates and for every two metal atoms, there is one carbonate ion.

   b. What information do you need to find the percent mass of an ion, like carbonate, in a compound?

   The total mass of the compound and the known mass of the ion are needed.

   c. Using the periodic table, find the percentage of carbonate by mass in each of the carbonates.

   Lithium carbonate (Li_2CO_3): _____81.2%_____

   Sodium carbonate (Na_2CO_3): _____56.6%_____

   Potassium carbonate (K_2CO_3): _____43.4%_____

   Cesium carbonate (Cs_2CO_3): _____18.4%_____

   Sample calculation:

   $$\frac{60.009 \text{ g/mol } CO_3}{73.891 \text{ g/mol } Li_2CO_3} \times 100 = 81.213\% \text{ of carbonate in lithium carbonate}$$

   d. Why is the percentage of carbonate different for each of the compounds listed above while the ratio of carbonate to metal ion is the same?

   Each metal has a different mass, affecting the mass percent of metal and carbonate in the compound.

   e. When identifying an unknown, why is it helpful to know the chemical percent composition?

   Each compound has a unique percentage of carbonate; this will help identify it.

MODEL 1

Building Model 1 – Precipitating an Unknown

1. Obtain four 100-mL beakers and label them "A," "B," "C," "D."

2. Add approximately 50 mL of distilled water to each beaker.

3. Into each of the 100-mL beakers add a *pea size* amount of Unknown A, which is an alkali metal carbonate.

4. Use a stirring rod to mix and dissolve the unknown carbonate.

❷ 5. In the beaker below draw the unknown carbonate solution as a particulate-level representation. Use the particulate key as a guide.

   NOTE: Use "M" when referring to the unknown alkali metal.
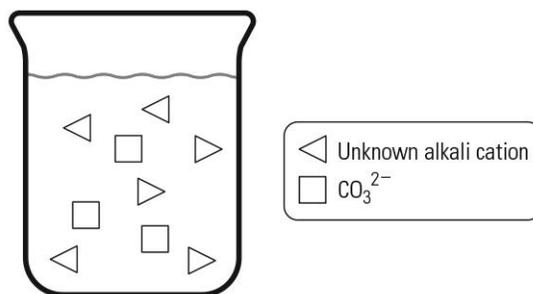
The particulate-level picture should be full of ions of M^+ and CO_3^{2-}. There should be twice the number of alkali atoms as carbonate molecules.

❷ 6. To determine the identity of the unknown, the mass of the unknown and the mass of carbonate in the unknown needs to be obtained. Brainstorm ways to separate the alkali metal ions from the carbonate ions.

   Considering the solubility of alkali metals, the best way to separate alkali metals from their respective anion is to simply dissolve them. Students may also suggest electrolysis.

7. Into Beaker A add 5 drops of 0.1 M $NaNO_3$.

8. Into Beaker B add 5 drops of 0.1 M NH_4NO_3.

9. Into Beaker C add 5 drops of 0.1 M $CaCl_2$.

10. Into Beaker D add 5 drops of 0.1 M KCl.

11. In the beakers in Model 1 draw particulate-level pictures of the resulting solutions in Beakers A-D. Use the particulate key as a guide.

Model 1 – Precipitating an Unknown
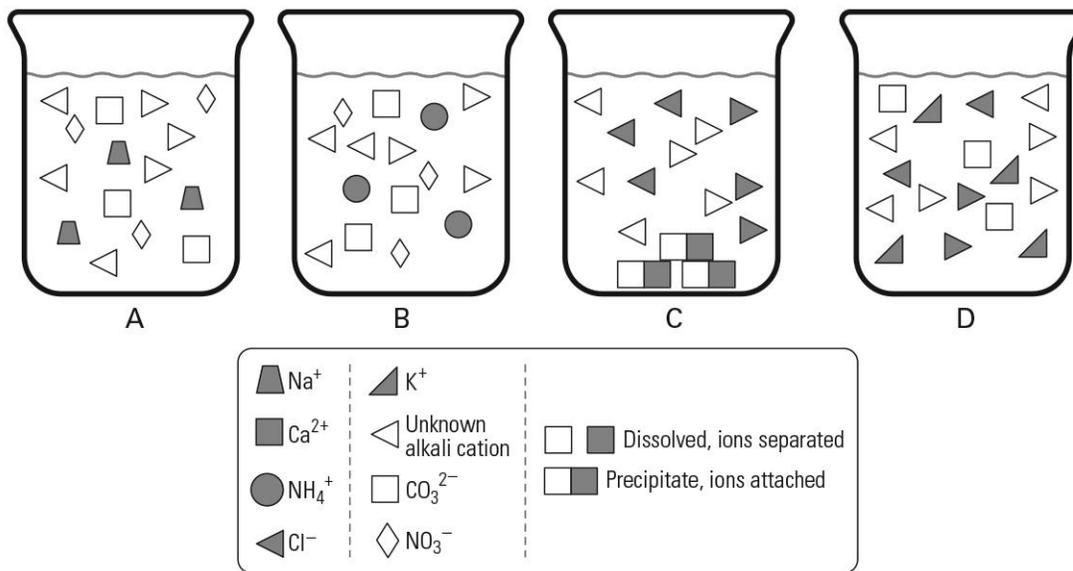
Unknown: K_2CO_3; Beaker A: $NaNO_3$ solution; Beaker B: NH_4NO_3 solution; Beaker C: $CaCl_2$ solution; Beaker D: KCl solution.

The particulate-level pictures for beakers A, B, and D should contain ions of all of the compounds, respectively. Beaker C should have M^+ and Cl^- as ions and the rest as a solid. There should be twice the number of unknown alkali cations and chlorine ions as solid particles.

Analyzing Model 1 – Precipitating an Unknown

12. Draw a particulate-level representation of the reaction that occurred in Beaker C. Start with three molecules of M_2CO_3, where "M" refers to the unknown alkali metal, and three molecules of $CaCl_2$. Use the particulate key as a guide. Please observe the Law of Conservation of Mass in your drawings.
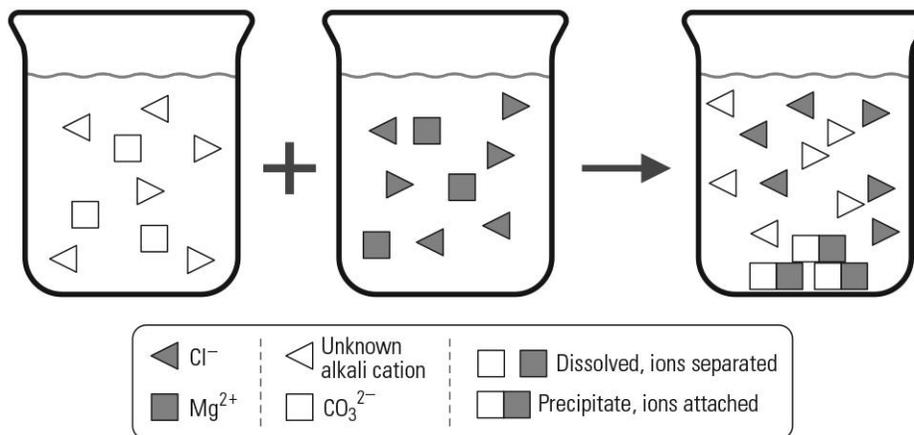
13. Use your drawings of the reaction in Beaker C to describe the pathway the carbonate molecules followed throughout this reaction.

Carbonate molecules are soluble in the beginning. Dissolved in water, they exist as ions. After the addition of $CaCl_2$, all the carbonate molecules are found in the precipitate.

MODEL 2

Building Model 2 – Finding the Mass of Carbonate in an Unknown

1. Place a clean 100-mL beaker on an analytical balance and tare the mass of the beaker.

2. Add approximately 1.00 g of your unknown carbonate into the beaker. Record the exact mass (to three decimal places) in the Model 2 Data Table.

3. Add 20 mL of distilled water and stir with a stirring rod until dissolved.

4. Add 30 ml of 0.25 M $CaCl_2$ to the solution containing the unknown carbonate and stir to dissolve.

5. Assemble a filtration setup as in the diagram to the right using the Erlenmeyer flask and funnel.

6. Write your initials on a piece of filter paper with a pencil. Record the mass (to three decimal places) of the dry filter paper in the Model 2 Data Table. Then fold the filter paper and place it into the funnel.

7. Slowly pour the contents of the beaker with your precipitate into the funnel. Do not overfill the filter paper.

8. Rinse the beaker and stirring rod with deionized water to ensure that all the precipitate is in the funnel.

9. Continue until all of the filtrate has moved through the filter paper into the flask.

❷ 10. What type of substance is small enough to pass through the filter paper?

The solvent, in this case, water and dissolved ions, can pass through the filter paper.

❷ 11. What type of substance is large enough to get caught in the filter?

Solids get caught in the filter paper.

❷ 12. How would the amount of your yield be affected if some of the carbonate was not precipitated?

The amount of yield would be lower.

❷ 13. Where would the non-precipitated ions be after the filtration is complete?

The non-precipitated ions would be in the filtrate in the Erlenmeyer flask.

14. In the filtration setup below, draw particulate-level pictures of the products being filtered. Use the particulate key as a guide.

Filter paper

Filter funnel

■ Ca^{2+}
□ $CO_3{}^{2-}$
◀ Cl^-
◁ Unknown alkali cation
▭ Precipitate, ions attached
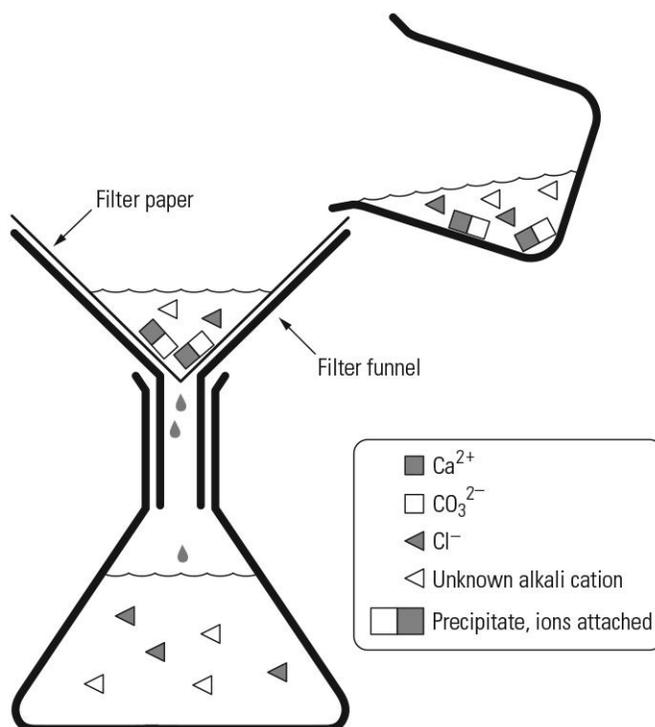
The particulate-level picture should be full of M^+ and Cl^- ions in the flask and in the filtrate above the filter paper, with solid $CaCO_3$ molecules on the filter paper. There should be twice the amount of unknown alkali metal and chlorine ions than solid particles. The symbolic representation should be MCl (aq) and $CaCO_3$ (s).

❷ 15. How can you determine if any carbonate ions went through the filter?

Add more $CaCl_2$ to the contents of the Erlenmeyer flask. If this causes further precipitation, carbonate ions were in the filtrate.

❷ 16. What action should you take if carbonate ions passed through the filter?

Add more $CaCl_2$ to precipitate any remaining carbonate and then slowly pour it through the filter again.

17. After you make sure all the carbonate has been removed from the filtrate, carefully place the wet filter paper with the $CaCO_3$ onto a watch glass and then into a drying oven overnight. This will remove any remaining water to ensure accurate mass measurements.

The Next Day

18. Remove the filter paper from the drying oven and measure its mass using an analytical balance. Record the mass (to three decimal places) in the Model 2 Data Table and determine the mass of the calcium carbonate precipitate.

Model 2 – Finding the Mass of Carbonate in an Unknown

Table 1: Model 2 Data Table – Finding the mass of carbonate in an unknown

Parameter	Mass (g)
Alkali metal carbonate (Unknown A)	1.044
Dry filter paper	0.987
Dry filter paper plus $CaCO_3$	1.740
$CaCO_3$	0.756

Analyzing Model 2 – Finding the Mass of Carbonate in an Unknown

19. Use the periodic table to determine the percentage of carbonate in calcium carbonate.

    $CaCO_3$ has a molar mass of 100.0869 g/mole and CO_3^{2-} has a molar mass of 60.0089 g/mole

    Using the sample data:

    $$\frac{60.0089 \ \frac{g}{mole} \ CO_3^{2-}}{100.0869 \ \frac{g}{mole} \ CaCO_3} \times 100 = 59.96\% \ CO_3^{2-}$$

20. Knowing the percentage of carbonate in $CaCO_3$ and the mass of calcium carbonate, find the mass of carbonate in the unknown alkali metal carbonate (Unknown A).

    Using the sample data:

    $0.756 \ g \ CaCO_3 \times 0.5996 = 0.453 \ g \ CO_3^{2-}$

21. Find the percentage of carbonate in the alkali metal carbonate using the mass of the carbonate from Unknown A in Model 2 and the total mass of the alkali metal carbonate.

    Using the sample data:

    $$\frac{0.453 \ g \ CO_3^{2-}}{1.044 \ g \ unknown} \times 100 = 43.39\% \ CO_3^{2-}$$

22. The possible unknown compounds in this lab include lithium carbonate, sodium carbonate, potassium carbonate, and cesium carbonate. Using the percentages calculated in the Getting Your Brain in Gear section of the lab, identify the unknown and explain why you are confident with the methods of data collection that lead you to this conclusion.

    The unknown is potassium carbonate.

    The percent composition of carbonate in the unknown, 43.39%, closely matches the percentage of carbonate of potassium carbonate in the "Getting Your Brain in Gear" question.

Connecting to Theory

When water quality is tested, a precipitate is intentionally formed. From the color of the precipitate, the identity of the dissolved ions can be determined. Chemists consult the Solubility Rules when they want to force ions to precipitate. The Solubility Rules are designed so that the user can cross reference cations with anions and determine if they will precipitate. Once the precipitate is formed, it can be dried and measured using gravimetric techniques.

Table 2: Abridged Solubility Rules

Ion	Solubility	Exceptions
NO_3^- (Nitrate)	Soluble	None
ClO_4^- (Chlorate)	Soluble	None
Halogens except F	Soluble	Ag^+, Hg_2^{2+}, Pb^{2+}
F^- (Fluoride)	Soluble	Ca^{2+}, Ba^{2+}, Sr^{2+}, Hg_2^{2+}, Pb^{2+}, Ag^+
SO_4^{2-} (Sulfate)	Soluble	Ca^{2+}, Ba^{2+}, Sr^{2+}, Hg^{2+}, Pb^{2+}, Ag^+
CO_3^{2-} (Carbonate)	Insoluble	Alkali Metals and NH_4^+
PO_4^{3-} (Phosphate)	Insoluble	Alkali Metals and NH_4^+
OH^- (Hydroxide)	Insoluble	Alkali Metals and Ca^{2+}, Ba^{2+}, Sr^{2+}
Alkali metals	Soluble	None
NH_4^+ (Ammonium)	Soluble	None

Applying Your Knowledge – Identifying an Unknown

An unknown alkali metal carbonate was discovered in a pharmacy. The pharmacist would like to identify it. If the unknown is lithium carbonate, it can be used as a drug to treat bipolar disorders. All other alkali carbonates: potassium carbonate, cesium carbonate, and sodium carbonate, will not be useful in treating this type of disorder.

Your lab group can use the following chemicals to identify the unknown:

- 2.0 g of unknown alkali metal carbonate

- 20.0 mL of the following solutions 0.5 M KNO_3, 0.5 M LiCl, 0.5 M $Ca(NO_3)_2$, and 0.5 M NaCl.

All other standard laboratory equipment is available. Consult your instructor with special requests. You do not need to use all of the materials provided.

1. Design a procedure to find the identity of the unknown.

   For the data collected below, after consulting the solubility rules in the Applying Your Knowledge section, 0.5 M $Ca(NO_3)_2$ was chosen to precipitate the carbonate as calcium carbonate.

2. Create a data table to organize your data.

   Applying Your Knowledge Data Table – Identifying the unknown

Parameters	Mass (g)	
	Trial 1	Trial 2
Unknown carbonate	0.4963	0.4933
Dry filter paper	0.8959	1.0055
Dry filter paper and $CaCO_3$	1.6583	1.7784
$CaCO_3$	0.7624	0.7729
Average mass	0.7677	

3. Before you start the lab, have your instructor approve your lab procedure for safety, but not on the accuracy of your proposed procedure.

Answers will vary.

4. Show the calculations needed to identify the unknown.

Answers will vary.

Using the sample data, the percentage of carbonate is:

$$0.7677 \text{ g CaCO}_3 \times 0.5996 = 0.4603 \text{ g CO}_3^{-2}$$

$$\frac{0.4603 \text{ g CO}_3^{-2}}{0.4963 \text{ g unknown}} \times 100 = 92.75\% \text{ CO}_3^{-2}$$

5. Did the pharmacist have lithium carbonate or a different compound? How did you come to this conclusion?

The pharmacist has lithium carbonate. The percentage of carbonate in the unknown is 92.75%, which is closest to the percentage of carbonate in lithium carbonate: 81.2%.

6. Discuss the limitations of the laboratory techniques you used and how you can improve the accuracy of your results. You may use diagrams to supplement your explanations.

Answers will vary.

- $CaCO_3$ can be lost in the transfer from the beaker to the filtration system.
- $CaCO_3$ needs to be dried thoroughly.

Teacher Tips

Tip 1 – Separate Stations

For the most efficient use of time and equipment, the class should be divided into small groups and cycled through the experimental procedure set up as three separate stations throughout the laboratory. Replicate stations for each part can be created for larger class sizes\

Tip 2 – Dry Samples
It is important that the student samples are completely dry before they obtain the final mass. To determine that the samples are dry, select several student samples and periodically determine their mass. Once no more mass is lost, the samples are dry. This applies to both Model 2 and the Applying Your Knowledge sections.

4. STOICHIOMETRY IN SOLUTIONS

Initial Question

When water is tested, chemists can tell you what impurities are present. If something harmful is found in your drinking water, like lead or cadmium, it is important to know how much is present. Hazardous particles put into your body faster than they can be removed will build up to toxic levels. There are several ways to determine the amount of dissolved particles in a solution. In this lab, you will explore one of them.

How is the amount of a dissolved substance determined?

Learning Objectives[*]

Students perform analytical techniques to determine the concentrations of dissolved ions.

LO 1.20 / The student can design, and/or interpret data from, an experiment that uses titration to determine the concentration of an analyte in a solution

LO 3.3 / The student is able to use stoichiometric calculations to predict the results of performing a reaction in the laboratory and/or to analyze deviations from the expected results.

LO   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.

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

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

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

Time Requirement

Preparation time: 30 minutes / Lab activity: 60 minutes

Materials and Equipment

Model 1, Model 2, and Applying Your Knowledge

- Data collection system
- Conductivity sensor[1]
- Fast-response temperature sensor
- Drop counter
- Drop dispenser:
  Syringe, 60-mL
  Stopcock (2)
  Drop tip
- Beaker, 250-mL
- Beaker, glass, 150-mL
- Graduated cylinder, 50-mL
- Mohr pipet, 25-mL

[1]Included with PASCO Advanced Chemistry Sensor

- Pipet pump
- Magnetic stirrer (stir plate)
- Micro stir bar
- Multi-clamp
- Ring stand
- Three-finger clamp
- Phenolphthalein, 3 drops
- 2.0 M Sodium hydroxide (NaOH), 120 mL
- Distilled water, 110 mL
- Wash bottle
- Materials for drop counter and pH sensor calibration (refer to Appendix A)

Model 1

- 1.0 M Hydrochloric Acid (HCl), 25.0 mL

Model 2

- Hydrochloric Acid (HCl), one of several possible concentrations, 25.0 mL

Applying Your Knowledge

- Monoprotic acid of an unknown concentration, 25.0 mL[1]

[1]Refer to the Lab Preparation section to prepare various concentrations of HCl.

Prerequisites

Students should be familiar with the following concepts:

- Thermochemistry
- Stoichiometric calculations
- Net ionic equations of acid–base reactions
- Limiting Reactants

Lab Preparation

These are the materials and equipment to set up prior to the lab:

Model 1, Model 2, and Applying Your Knowledge

1. **2.0 M Sodium hydroxide (NaOH):** To prepare 1000 mL of 2.0 M sodium hydroxide (NaOH), fill a 1000-mL volumetric flask 1/3 full of distilled water. Add 79.994 g of sodium hydroxide to the flask and swirl it to dissolve the contents. Stir it well and let it sit to cool. Fill the flask to the line with distilled water. Depending on the number of student groups in the class, one liter may be needed for each model.

Model 1

2. **1.0 M Hydrochloric acid:** To prepare 1000 mL of 1.0 M hydrochloric acid (HCl), fill a 1000-mL volumetric flask 1/3 full of distilled water. Add 83.3 mL of concentrated hydrochloric acid (12 M) to the flask and swirl. Fill to the line with distilled water.

Model 2 and Applying Your Knowledge

NOTE: In Model 2 and Applying Your Knowledge, several concentrations of HCl are to be reacted with 2.00 M NaOH. Determine which concentrations to use between 0.5 and 2.0 M HCl and assign a concentration to each student group so all concentrations are tested. For Model 2, students share the data for the reactions they haven't done.

Any concentration between 0.5–2.0 M HCl, other than 1.0 M HCl for Model 2, will work. Below is the preparation for 1.5 M HCl. Adjust the volume to obtain other concentrations.

3. **1.5 M Hydrochloric acid (HCl):** To prepare 1000 mL of 1.5 M hydrochloric acid (HCl), fill a 1000-mL volumetric flask 1/3 full of distilled water. Add 125.0 mL of concentrated hydrochloric acid to the flask and swirl. Fill the flask to the line with distilled water.

    NOTE: For Applying Your Knowledge, label the solutions "Unknown A," "Unknown B," and so on, keeping track of the concentration of each one.

Safety

Add these important safety precautions to your normal laboratory procedures:

- This lab uses strong acids and bases. In case of contact with your skin, wash off the solution with a large amount of water.

Getting Your Brain in Gear

1. Identify each of the following substances as an acid or a base.

HCl:	acid
H_2SO_4:	acid
KOH:	base
NaOH:	base
HNO_3:	acid

2. In the beakers below, draw particle-level representations showing a strong acid and a strong base dissolved in water.
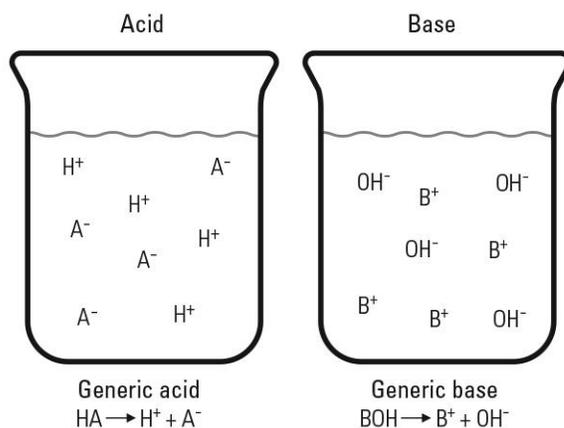
3. Describe the procedure you would use to make 100 mL of 0.85 M HCl from a 2.0 M HCl solution. Assume you have a 100-mL volumetric flask, distilled water and a 50-mL graduated cylinder available.

First, calculate the volume of the 2.0 M HCl solution needed using the equation $M_1V_1 = M_2V_2$:

(2.0 M HCl)(V_1) = (0.85 M)(0.100 L)

V_1 = 0.0425 L = 42.5 mL ≈ 43 mL

Pour about 25 mL of distilled water into the volumetric flask. Use the graduated cylinder to measure 43.0 mL of 2.00 M HCl solution. Add the HCl solution to the volumetric flask and mix. Fill the flask to the mark with distilled water.

4. List three pieces of evidence that indicate a chemical reaction has taken place.

Evidence of a chemical reaction includes color change, change in temperature, change in pressure, change in conductivity, and change in pH.

MODEL 1

Building Model 1 – Using a Strong Acid and Strong Base

1. Start a new experiment on the data collection system.

2. Connect a conductivity sensor, a fast-response temperature sensor, and a drop counter to the data collection system.

3. Display both temperature and conductivity on the *y*-axis of a graph and fluid volume on the *x*-axis.

4 Use the multi-clamp to attach the drop counter to the ring stand. Use the illustration as a guide.

5. Use the three-finger clamp to attach the drop dispenser to the ring stand.

6. Rinse the drop dispenser syringe:

   a. Place a 250-mL beaker under the drop dispenser and open both stopcocks.

   b. Rinse the drop dispenser syringe and stopcock three times with approximately 20 mL of distilled water. This will remove any residue.

   c. Rinse the drop dispenser three times with 20 mL of the 2.0 M NaOH. This removes remaining water that would dilute the NaOH solution.

   d. Discard the rinse solution as directed by your teacher.

7. Calibrate the drop counter using the instructions in Appendix A.

   NOTE: Do not disconnect the drop counter from the data collection system or it will need to be calibrated again.

8. Use the top stopcock to adjust the flow rate to approximately 1 drop per second. Close the bottom stopcock and fill the syringe to the top mark with the 2.0 M NaOH solution.

   NOTE: The top valve controls the flow rate and the bottom valve turns the flow on and off.

9. Assemble the rest of the apparatus, using the steps below and the illustration as a guide.

   a. Position the magnetic stir plate on the base of the ring stand.

   b. Position the drop counter over the magnetic stir plate.

   c. Place the temperature sensor though the small hole in the drop counter.

   d. Place the conductivity sensor, with the micro stir bar attached, through a large hole in the drop counter.
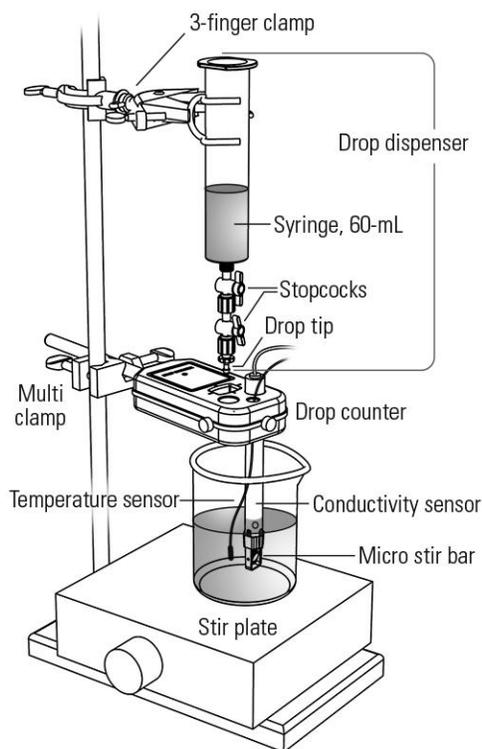
10. Using a Mohr pipet, transfer 25.0 mL of 1.0 M HCl solution to a clean, dry 150-mL beaker. Record the molarity and volume in the Model 1 Data Table.

11. Add 50.0 mL of distilled water to the beaker.

❷ 12. Calculate the number of moles of acid added to the beaker.

1.0 M HCl × 0.0250 L = 0.025 moles of HCl added

❷ 13. Calculate the molarity of the solution after the 50.0 mL of distilled water is added.

$$\frac{0.025 \text{ mol HCl}}{(25.0 \text{ mL} + 50.0 \text{ mL})} \times \frac{1000 \text{ mL}}{1 \text{ L}} = 0.33 \text{ M HCl}$$

❷ 14. Calculate the number of moles of acid after the 50.0 ml of distilled water is added.

$$\frac{0.33 \text{ mol HCl}}{\text{L}} \times \frac{0.075 \text{ L}}{1} = 0.025 \text{ mol HCl}$$

❷ 15. Does adding distilled water change the molarity or the number of moles of acid? Explain your answer.

The molarity changed but the number of moles of acid did not change, as shown by comparing the previous answers.

16. Put 3 drops of phenolphthalein indicator into the beaker with the HCl solution.

NOTE: Phenolphthalein is a dye that changes color in the presence of a base.

17. Place the 150-mL beaker with the hydrochloric acid solution under the drop dispenser. The sensors should be immersed in the solution. Turn on the magnetic stirrer at a slow and steady rate.

18. Start recording data.

19. Open the bottom stopcock on the drop dispenser to begin the flow of the 2.0 M NaOH into the HCl solution.

20. In the Model 1 Data Table, record the volume of titrant used when the phenolphthalein indicator changes color.

21. Continue until approximately 20 mL of NaOH solution has been added to the beaker.

22. Stop recording data.

23. Save your experiment and dispose of the used solutions according to your teacher's instructions.

24. Sketch or attach a copy of your graph of Temperature and Conductivity vs Volume of HCl in the space provided in Model 1.

Model 1 – Using a Strong Acid and Strong Base

Table 1: Model 1 Data Table—End point determination

Parameter	Value
Concentration of HCl (M)	1.0
Volume of 1.0 M HCl solution (mL)	25.0
Concentration of NaOH used (M)	2.0
Volume of NaOH added to change the color of the solution (mL)	12.8

Temperature and conductivity vs volume of NaOH
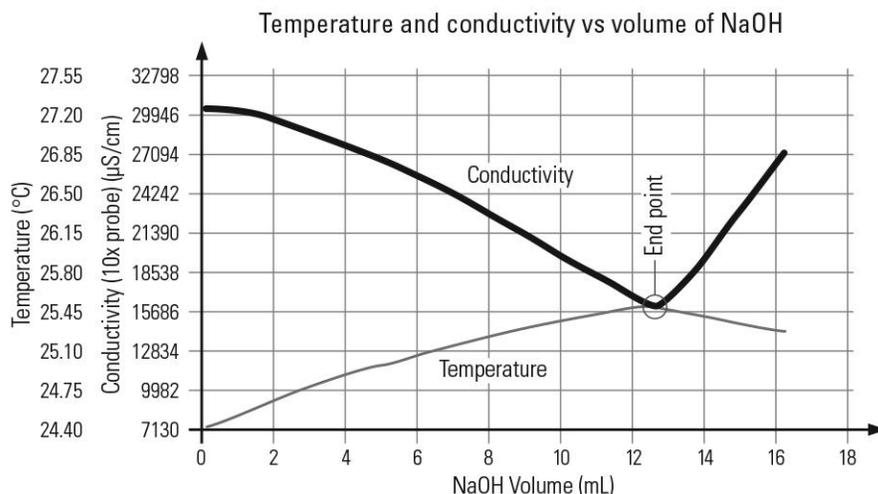
Analyzing Model 1 – Using a Strong Acid and Strong Base

25. Write the balanced chemical equation for the reaction in Model 1.

    $HCl + NaOH \rightarrow NaCl + H_2O$
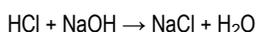
26. The point where the solution changes color is called the *end point*. What was the volume of 2.0 M NaOH required to reach the end point of the reaction? Label this point on the graph.

    The volume of NaOH added is 12.8 mL.

27. Complete Table 2 with the volume, molarity, and number of moles of acid and base when the end point is reached.

    Table 2: Amount of reactants

Solution	Molarity (M)	Volumes (mL)	End Point Amount (mol)
HCl (analyte)	1.0	25.0	0.025
NaOH (titrant)	2.0	12.8	0.026

    Example calculations to determine the amount of HCl and NaOH that reacted:

    1.0 M HCl × 0.0250 L = 0.0250 moles HCl

    2.0 M NaOH × 0.0128 L NaOH = 0.0256 moles NaOH

28. In this procedure the color change end point is also the *equivalence point*. What is equal at the equivalence point?

    The point where the number of moles of acid in the beaker equals the number of moles of base added.

29. Look at your graph in Model 1. Does the temperature plot indicate a clear change at the equivalence point? If yes, describe the shape of the curve at the equivalence point.

    Yes. The temperature increased until the equivalence point and then decreased after the equivalence point.

30. Write the word "energy" on the appropriate side of the balanced equation. Explain your answer.

$$\underline{\hphantom{XXXXXXXXXXX}} \quad \text{HCl} + \text{NaOH} \rightarrow \text{NaCl} + \text{H}_2\text{O} \quad \underline{\hphantom{XX} + \text{energy} \hphantom{XX}}$$
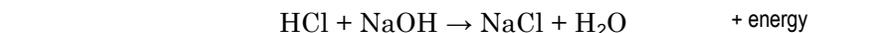
    The temperature is increasing as long as a reaction is occurring, so the reaction is exothermic.

31. This reaction is very fast. Assume that the reaction reaches completion after each drop of titrant is added.

    a. Once the reaction is past the equivalence point, will excess reactant continue to have an effect on the change in temperature? Explain your response.

       No, after the equivalence point, the temperature decreased at a steady rate, since there was no reaction occurring.

    b. Describe the region of the Model 1 graph where NaOH is the limiting reactant in the reaction.

       NaOH is the limiting reactant prior to the equivalence point, when the temperature is increasing. In this region, each addition of NaOH reacts with the HCl and causes an increase in temperature.

    c. Describe the region of the Model 1 graph where HCl is the limiting reactant in the reaction.

       HCl is the limiting reactant when the temperature is decreasing. After the equivalence point, all of the HCl has been consumed and no reaction occurs. The addition of NaOH does not cause any further increase in temperature.

32. Look at your graph in Model 1. Explain, based on the equation and the limiting reactant, why there is a change in the temperature curve around the equivalence point.

    When the temperature is increasing, the molecules of HCl and NaOH are reacting and releasing energy as heat. By the equivalence point, the limiting reactant has been completely consumed, so the temperature no longer increases and starts to cool to room temperature.

33. The chemical equation for a reaction can be re-written in ionic forms to indicate the actual substances that are reacting. Write both the complete equation and the net ionic equation for the reaction in Model 1.

    Complete equation: $\text{H}^+ + \text{Cl}^- + \text{Na}^+ + \text{OH}^- \rightarrow \text{H}_2\text{O} + \text{Na}^+ + \text{Cl}^-$

    Net ionic equation: $\text{H}^+ + \text{OH}^- \rightarrow \text{H}_2\text{O}$
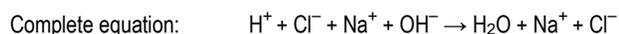
34. Look at your graph in Model 1. Does the conductivity plot indicate a clear change at the equivalence point? If yes, describe the shape of the curve at the equivalence point.

    Yes. The conductivity decreased until it reached the equivalence point and then increased after it.

35. Explain the change in conductivity before the equivalence point, based on the species in the beaker.

    Before the equivalence point, OH^- ions reacted with the H^+ ions to produce water, removing the ions and decreasing the conductivity.

36. Explain the change in conductivity after the equivalence point, based on the species in the beaker.

    After the equivalence point has been reached, the addition of Na^+ and OH^- ions increases the conductivity in the solution.

37. Draw a particulate level representation of the substances in the beaker before the experiment, at the equivalence point, and at the end of the experiment.
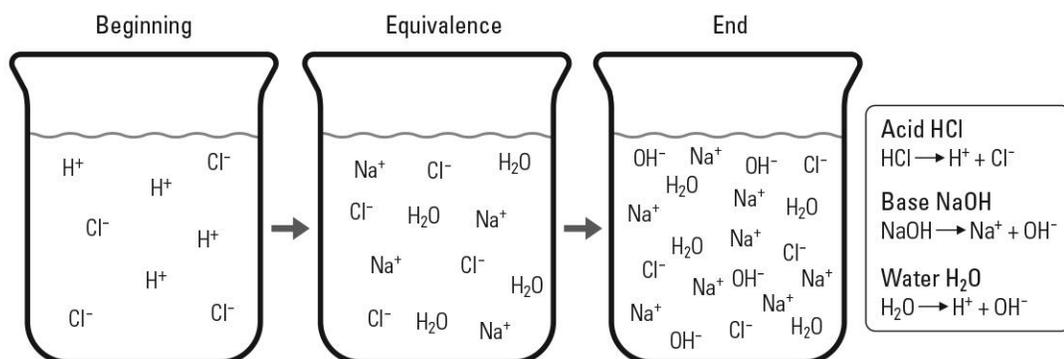
38. Did the color-change end point occur at the same volume of NaOH as the change in the temperature graph and the conductivity graph? If not, provide some reasons for the discrepancy.

Students should find that the end point detected by the color change of the phenolphthalein occurred at the equivalence point on the graph. If it did not, this could be due to adding too much or too little NaOH or mismeasuring the amount of acid.

39. Phenolphthalein, a temperature sensor, and a conductivity sensor were all used to determine when the reaction was complete. For the following reactions, which would work best? Explain your reasoning.

a. A reaction in which a precipitate is formed.

The conductivity sensor would work best. The formation of the precipitate causes a decrease in conductivity as the precipitate forms, and conductivity would increase after the equivalence point. Phenolphthalein could be used if the acidity of the chemical species changes.

b. A reaction that is endothermic.

The temperature sensor would work best. The temperature decreases as the reaction proceeds. After the equivalence point, the temperature increases to room temperature. Phenolphthalein could be used if the acidity of the chemical species changes.

c. A reaction in which one of the products has a dark color.

Depending on the reaction, either the temperature or conductivity can be used. Phenolphthalein could not be used as the dark color would mask the color change.

MODEL 2

Building Model 2 – Varying Concentration

1. Set up the equipment as you did for Model 1.

2. Start a new experiment on the data collection system, as you did in Model 1.

3. Rinse and fill the drop dispenser with 2.0 M NaOH.

4. If the drop counter has been disconnected from the data collection system since it was last calibrated, calibrate it using the procedure in Appendix A.

5. Your instructor will give you a sample of HCl to react with the 2.0 M NaOH. Record its concentration in Model 2.

6. Using a Mohr pipet, transfer 25.0 mL of the HCl solution into a clean, dry 150-mL beaker. Record the molarity and volume in the Model 2 Data Table.

7. Add 50.0 mL of distilled water to the beaker.

❷ 8. Calculate the number of moles of acid added to the beaker.

Assuming a 1.5 M concentration: 1.5 M HCl × 0.0250 L = 0.0375 moles HCl

Answers will vary based on the concentration of acid given to the student group.

❷ 9. Calculate the molarity of the solution after the 50.0 mL of distilled water is added.

Assuming a 1.5 M concentration: $\dfrac{0.0375 \text{ mol HCl}}{(25.0 \text{ mL} + 50.0 \text{ mL})} \times \dfrac{1000 \text{ mL}}{1 \text{ L}} = 0.50$ M HCl

❷ 10. Calculate the number of moles of acid after the 50.0 mL of distilled water is added.

Assuming a 1.5 M concentration: $\dfrac{0.50 \text{ mol HCl}}{\text{L}} \times \dfrac{0.075 \text{ L}}{1} = 0.0375$ mol HCl

❷ 11. How many moles of NaOH will be required to reach the equivalence point with your sample of hydrochloric acid?

Assuming a 1.5 M concentration: 0.0375 moles NaOH

❷ 12. What volume of 2.0 M NaOH will be required to reach the equivalence point with your sample of hydrochloric acid?

Assuming a 1.5 M concentration: $0.0375 \text{ mol} \times \dfrac{1 \text{ L}}{2.0 \text{ mol}} = 0.01875 \text{ L} \approx 19$ mL HCl

13. Put 3 drops of phenolphthalein indicator into the beaker with HCl solution.

❷ 14. On the graph below, sketch the expected Temperature and Concentration vs Volume of NaOH curves for your sample of hydrochloric acid. Indicate the point on the graph where you expect the end point to occur.

The equivalence point and end point should occur on the graph at the volume of 2.00 M NaOH calculated above. For this example, it is 19 mL (refer to the graph in Model 2). The shape of the curves should be similar to the graph for Model 1.

Temperature and conductivity vs volume of NaOH

NaOH Volume (mL)
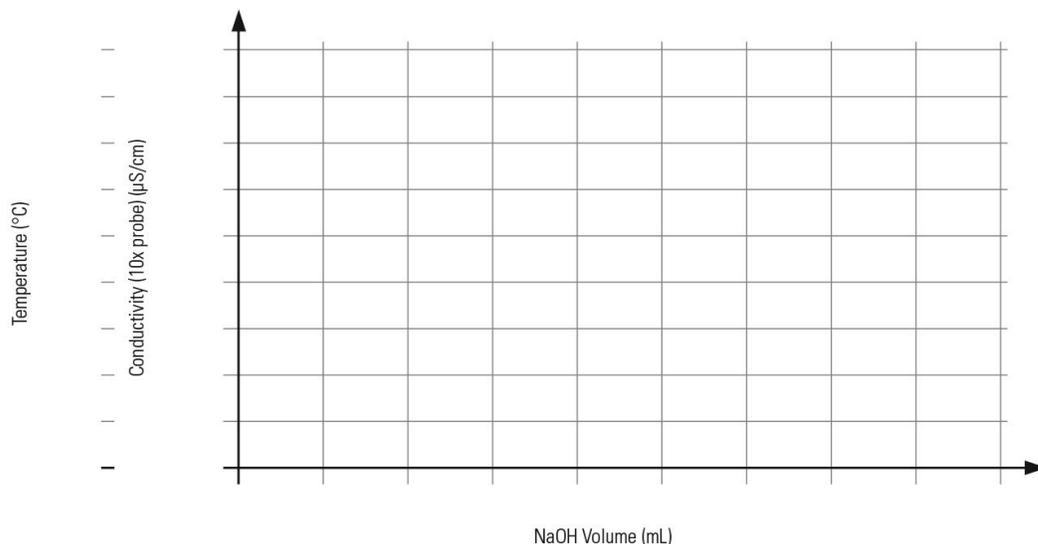
15. Place the 150-mL beaker with the hydrochloric acid solution under the drop dispenser. Turn on the magnetic stirrer at a slow and steady rate.

16. Start recording data.

17. Turn the drop dispenser stopcock carefully, allowing the titrant (2.0 M NaOH) to drip slowly (1 to 2 drops per second) into the HCl solution.

    NOTE: The top valve controls the flow rate and the bottom valve turns the flow on and off.

18. In the Model 2 Data Table, record the volume when the phenolphthalein indicator changes color.

19. Add NaOH until the equivalence point has been reached and exceeded.

20. Stop recording data.

21. Save your experiment and dispose of the used solutions according to your teacher's instructions.

22. Sketch or attach a copy of your graph of temperature and conductivity vs volume of HCl and paste it into Model 2.

Model 2 – Varying Concentration

Table 3: Model 2 Data Table—End point determination

Parameter	Value
Concentration of HCl sample (M)	1.5
Volume of 1.0 M HCl solution (mL)	25.0
Concentration of NaOH used (M)	2.0
Volume of NaOH added to change the color of the solution (mL)	19

Temperature and conductivity vs volume of NaOH
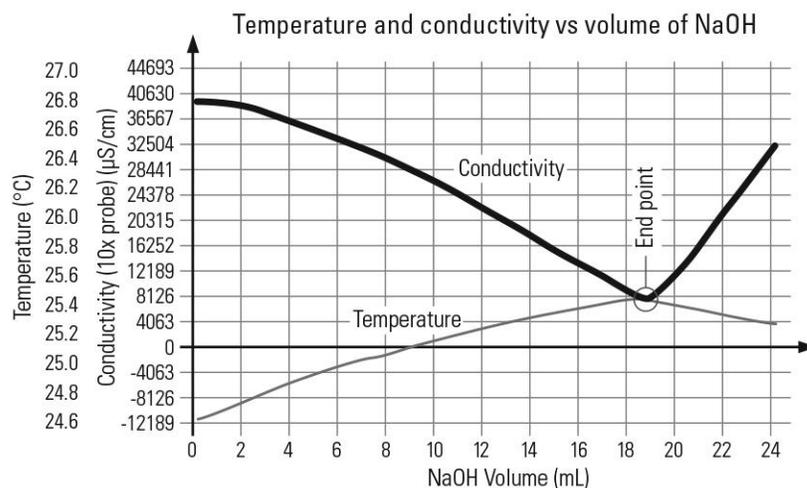
Analyzing Model 2 – Varying Concentration

23. How did your predicted graph compare to the experimental graph?

    Ideally, students should find that the equivalence point and end point (color-change point) are close to the calculated values. The slopes of each plot and the temperature and conductivity at the equivalence point may be different from the predicted graph.

24. Compare your graph to those of other students with different concentrations of HCl. What is the same for each of the graphs? What is different?

    The graphs have the same general shapes, but they have different equivalence points and end points, depending on the concentration of their acid sample. The temperature and conductivity ranges should also be different for different acid concentrations.

25. What variable affected the volume of 2.0 M NaOH required to reach the equivalence point?

    The molarity of the acid changed the number of moles of HCl that reacted with the NaOH.

26. What other variable could affect the volume of 2.0 M NaOH required to reach the equivalence point? Explain.

    The volume of acid of a specified molarity added. Both molarity and volume determine the amount of moles that react.

Connecting to Theory

The technique in this lab is called *titration*. It is a powerful analytical technique that uses a substance with a known concentration to determine the concentration of a solution with an unknown concentration. Titrations are most often used with indicators or with a pH sensor. As you have experienced, other types of measurements can be used.

This technique is most often used to answer the question, "How much of a dissolved substance is in a sample?"

Applying Your Knowledge – Determining an Unknown Concentration

You will be given an unknown concentration of a strong monoprotic acid. Design an experiment to determine the concentration of the acid using 2.0 M NaOH. After your teacher has approved it, carry out your experiment.

Be prepared to make a presentation to the class that includes the following:

1. Your resulting data and graph.

2. Depending on the design of your experiment, provide one or more of the following:

   a. An explanation of how the indicator end point of the titration compared to the indicator end point in Models 1 and 2.

   b. An explanation of how the temperature curve for your reaction compares to the temperature curve of HCl and NaOH in Models 1 and 2.

   c. An explanation of how the conductivity curve for your reaction compares to the conductivity curve of HCl and NaOH in Models 1 and 2.

3. The concentration of the unknown acid with calculations that support your answer.

4. The percent error of your unknown concentration and sources of error. Ask your instructor for the actual concentration of your solution.

$$\%\text{Error} = \frac{\left|\text{Actual concentration} - \text{Your concentration}\right|}{\text{Actual concentration}} \times 100$$

5. POLAR AND NONPOLAR SUBSTANCES

Initial Question

Some things dissolve in water, some do not. If you want to dissolve permanent marker ink, for example, you'll need something oily. Why? What is the difference in the chemical structure of a waterproof ink and one that washes off the paper at the first hint of moisture?

How does the polarity of a compound affect its solubility in different solvents?

Learning Objectives[*]

Students understand how a compound's structure influences its solubility in water and oil. They apply this knowledge to extract polar and nonpolar compounds from a mixture.

LO 2.8 / The student can draw and/or interpret representations of solutions that show the interactions between the solute and solvent.

LO 2.13 / The student is able to describe the relationships between the structural features of polar molecules and the forces of attraction between the particles.

SP 1.4 / The student can *use representations and models* to analyze situations or solve problems qualitatively and quantitatively.

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

SP 6.1 / The student can *justify claims* with evidence.

SP 6.2 / The student can *construct explanations of phenomena* based on evidence produced through scientific practices.

Time Requirement

Preparation time: 40 minutes / Lab activity: 60 minutes

Materials and Equipment

Model 1

- Data collection system
- pH sensor
- Beaker (5), 100-mL
- Stirring rod
- Beral pipet
- Mineral oil, 30 mL
- Distilled water, 30 mL
- Colored pencils or camera
- **Set 1 Compounds**
  Copper(II) sulfate ($CuSO_4 \cdot 5H_2O$), 0.5 g
  Iron(III) chloride ($FeCl_3$), 0.5 g
  Cobalt(II) chloride ($CoCl_2$), 0.5 g

- Beta-carotene ($C_{40}H_{56}$, carrot pigment), 10 mL[1]
- Capsanthin ($C_{40}H_{56}O_3$, paprika pigment), 10 mL[1]
- Riboflavin ($C_{17}H_{20}N_4O_6$, vitamin B), 10 mL[1]
- Lycopene ($C_{40}H_{56}$, tomato pigment), 10 mL[1]
- Betanin ($C_{24}H_{27}N_2O_{13}$, beet pigment), 10 mL[1]
- **Set 2 Compounds**
  Acetylsalicylic acid ($C_9H_8O_4$), 10 mL[1]
  Stearic acid ($C_{17}H_{35}COOH$), 0.5 g
  Oleic acid ($C_{17}H_{33}COOH$), 10 mL[1]
  Acetic acid (CH_3COOH), 10 mL[1]
  Citric acid ($C_6H_8O_7$), 0.5 g[1]

[1]To formulate these solutions from raw carrots, powdered paprika, vitamin B tablets, canned tomatoes, canned beets, and aspirin tablets, refer to the Lab Preparation section.

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Model 2

- Beaker (2), 100-mL
- Mineral oil , 20 mL
- Lycopene ($C_{40}H_{56}$, tomato pigment), 10 mL[1]
- Betanin ($C_{24}H_{27}N_2O_{13}$), beet pigment), 10 mL[1]

[1]To formulate these solutions, refer to the Lab Preparation section.

Prerequisites

Students should be familiar with the following concepts:

- Lewis dot structures
- Molecular and ionic compounds
- Polar and nonpolar molecules
- Intermolecular forces, particularly hydrogen bonding and London dispersion forces

Lab Preparation

These are the materials and equipment to set up prior to the lab. For long term storage, solutions should be transferred to glass containers (the oil soluble compounds in particular may stain plastic bottles).

NOTE: In Model 1, a number of compounds are tested. From each Compound Set, assign one compound to each student group so all compounds will be tested. Students share the data for the compounds they haven't studied

Model 1 – Set 1 Compounds

NOTE: To shorten preparation time, use a blender or food processor.

1. **Beta-carotene**: Grate or puree two large carrots. Place them in a 600-mL beaker and add about 150 mL (or 10 mL per group) of mineral oil. Cover with a watch glass or plastic wrap and allow it to sit for a day. Strain with a sieve or coffee filter, or gravity filter with filter paper. Decant the oil layer, which contains extracted beta-carotene, and which should be orange.

   NOTE: Mineral Oil: Students are directed to test their compounds in a mixture of water and mineral oil. Inexpensive mineral oil can be purchased at hardware stores in large quantities. You can also use baby oil if you don't mind the fragrance. If necessary, vegetable oil can be used, but it has a slight color and odor.

2. **Capsanthin**: Place 1 tablespoon of ground paprika or chili powder in a 600-mL beaker. Cover the powder with 150 mL (or 10 mL per group) of mineral oil. Stir well and allow it to sit for one hour. Decant the solution, which should be a deep orange, almost red color.

3. **Riboflavin**: Crush one vitamin B or riboflavin supplement tablet with a mortar and pestle. Place the powder in a 600-mL beaker and add 150 mL of water (or 10 mL per group). Stir well, cover with a watch glass or plastic wrap, and allow it to sit for one hour. Decant the solution.

4. **Lycopene**: Crush one small tomato in a 600-mL beaker and add about 150 mL (or 10 mL per group) of ethanol. Cover with a watch glass or plastic wrap and allow it to sit for a day. Strain with a sieve or coffee filter, or gravity filter with filter paper. The alcohol solution should be a light orange color.

   NOTE: Ethanol versus isopropanol: Isopropanol ("rubbing alcohol"), which can be obtained at drugstores, was also tested for the extraction of lycopene from tomatoes, but the oil and water mixtures in Model 2 separated very slowly (approximately 1 day compared to about 5 minutes for ethanol). If you substitute isopropanol for ethanol, realize that students may need to let their extractions sit overnight to obtain clear results.

5. **Betanin**: Decant the liquid from one 8 oz can of beets. Dilute it with distilled water until you have 150 mL (or 10 mL per group).

Model 1 – Set 2 Compounds

6. **Acetylsalicylic acid**: Crush two standard (300 mg) or 6 low dose (81 mg) aspirin tablets in a mortar and pestle. Place the powder in a 600 mL beaker and cover with 150 mL (or 10 mL per group) of ethanol. Stir well, cover with a watch glass or plastic wrap and allow it to sit for one hour. Decant the solution.

7. **Oleic acid**: Use olive oil, 10 mL per group.

8. **Acetic acid**: Use vinegar, 10 mL per group.

9. **Citric acid**: Purchase as solid citric acid from a chemical supply company or grocery store

Model 2

10. **Lycopene and betanin**: Prepare as for Model 1. Each group needs 10 mL of each compound.

Safety

Add these important safety precautions to your normal laboratory procedures:

- Many of the solutions used in this lab are alcohol based and are therefore flammable. They should not be used near an open flame or ignition source.

- Even though many of the compounds in this lab are "kitchen" items, treat all materials in this activity as hazardous.

Getting Your Brain in Gear

1. What is the difference between a compound and a mixture? Give two examples of each.

    Compounds have set ratios of atoms and those atoms are bonded by covalent or ionic bonds. Examples: $CuSO_4$, H_2O.

    Mixtures can have any ratio between their components. They may have intermolecular attractions, but not true covalent or ionic bonds. Examples: Lemonade, soil, soda.

2. Some molecules are too large to represent as Lewis dot structures. However, there is a simple "code" chemists often use to draw them. Below is the Lewis dot structure of aspirin, drawn two ways. Determine the rule to turn a Lewis structure into the "skeleton" structure on the right.
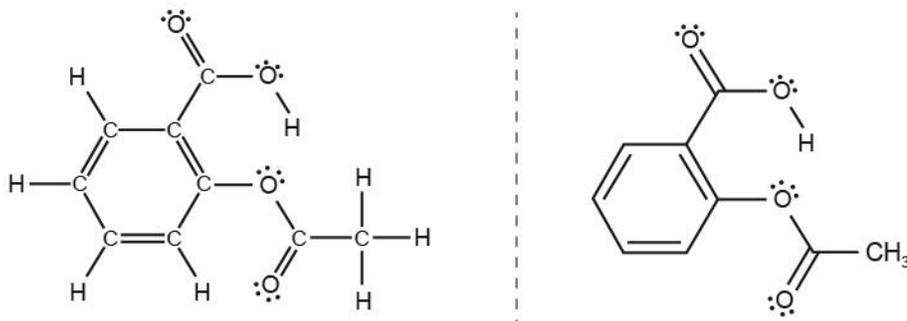
    Each point or vertex represents a carbon atom. Generally, hydrogen atoms bonded to carbon atoms are not drawn.

3. How many carbon atoms are in the following molecule?

    40
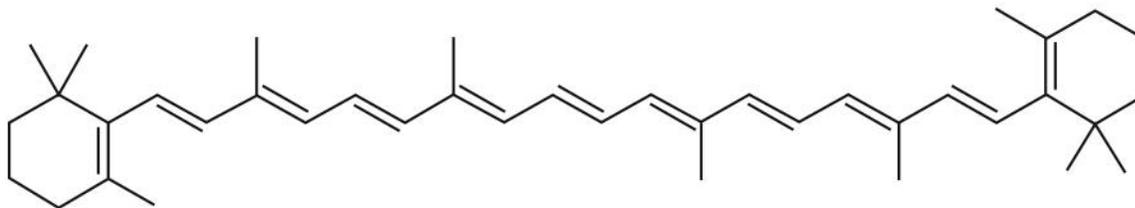
4. Circle all of the atoms or groups of atoms in the aspirin molecule that could form hydrogen bonds with water.
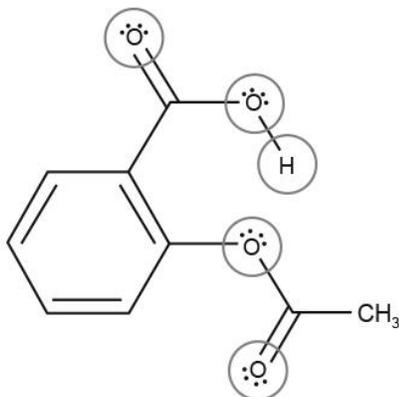
5. While some acids may dissolve in water, others do not. How would measuring the pH before and after the acid is added to water help determine if the acid dissolves in water?

    If the pH decreases, then that acid dissolves in water. If the pH remains (more or less) the same, that acid does not dissolve in water.

MODEL 1

Building Model 1 – Dissolving Compounds

1. Your teacher will assign you one compound from the Set 1 Compounds in the Materials and Equipment list. The compound may already be dissolved in a solvent or may be provided as a solid powder. Obtain about 10 mL of your assigned compound if it is a solution or a small scoop (approximately 0.5 g) if it is a solid.

2. In a 100-mL beaker, mix 10 mL of distilled water and 10 mL of mineral oil.

❷ 3. The density of water is about 1.00 g/mL and the density of mineral oil is about 0.85 g/mL. In the mixture you just made, which layer is on top and which is on bottom?

   The denser water layer is on the bottom, the less dense oil layer is on the top.

4. Add your assigned compound to the oil–water mixture. Stir with a stir rod for about 10 seconds.

5. Allow the mixture to sit for about 5 minutes. Determine which solvent your compound dissolves in best. In the Set 1 Compounds Results section below, use colored pencils or a photograph to record your observations. Label the layers.

6. Dispose of all mixtures in the proper waste containers and wash the beakers thoroughly with soap.

7. Your teacher will now assign you a compound from the Set 2 Compounds in the Materials and Equipment list. Obtain 10 mL of the assigned solution or a small scoop (approximately 0.50 g), if it is a solid.

❷ 8. Consider this new substance. Can you use the same method (dissolving the compound in a beaker with water and mineral oil) to test if it will dissolve in oil or water? Why or why not? If not, suggest a method or test that could be performed to determine in which solvent the compound dissolves.

   No, the same method can not be used because these compounds have no color. You cannot use naked eye observations. A pH sensor would be the best choice to detect whether or not the compound dissolves in the water because all of the substances are acids.

9. In a 100-mL beaker, mix 10 mL of distilled water and 10 mL of mineral oil. Allow this mixture to sit for 10 minutes while you perform the next step. This is the control.

10. In a second 100-mL beaker, mix 10 mL of distilled water, 10 mL of mineral oil and either 10 mL or a small scoop of your assigned compound. Mix with a stirring rod or by swirling the beaker. Allow this to sit for 10 minutes.

11. Connect a pH sensor to the data collection system.

12. For each of the oil–water mixtures, including the control, use a beral pipet to transfer some of the water layer to a clean beaker. Transfer enough to submerge the pH meter into the sample. Measure the pH of the water layer and record the results in the Model 1 Data Table.

   NOTE: Mixing water with oil may make the water slightly more acidic. It is therefore important to measure the pH of the oil–water control to determine the extent of this effect. If the acid dissolves in the water layer, expect a significant change (2 or more pH units) from the control.

13. Determine if the compound dissolved mostly in water or oil and place an "X" in the appropriate column of the Model 1 Data Table.

14. Rinse your pH probe well, first with soapy water and then with distilled water.

15. Rinse all of your glassware well, first with soapy water and then with distilled water.

16. Share your data with the class to complete the Model 1 Data Table.

Model 1 – Dissolving Compounds

Set 1 Compounds Results

Assigned compound: β-Carotene

OBSERVATIONS

The examples show a polar and nonpolar compound:

Nonpolar

❶ Oil / Yellow

❷ Water / Clear

Beta-Carotene

Polar

❶ Oil / Clear

❷ Water / Clear

Riboflavin
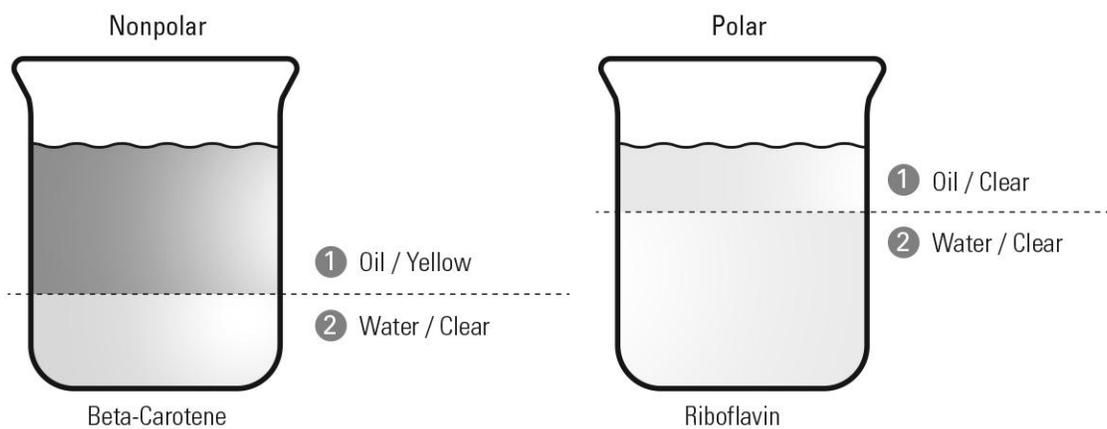
Set 2 Compounds Results

Assigned compound: _____Acetylsalicylic acid_____

Table 1: Model 1 Data Table—Properties of various compounds

Compound	pH of Water Layer	Dissolved in Water	Dissolved in Oil
Set 1 Compounds			
Copper(II) sulfate, $CuSO_4$		X	
Cobalt(II) chloride, $CoCl_2$		X	
Iron(III) chloride, $FeCl_3$		X	
Beta-carotene, $C_{40}H_{56}$			X
Capsanthin, $C_{40}H_{56}O_3$			X
Riboflavin, $C_{17}H_{20}N_4O_6$		X	
Lycopene, $C_{40}H_{56}$			X
Betanin, $C_{24}H_{27}N_2O_{13}$		X	
Set 2 Compounds			
Acetylsalicylic acid, $C_9H_8O_4$	4.42	X	
Stearic acid, $C_{17}H_{35}COOH$	7.55		X
Oleic acid, $C_{17}H_{33}COOH$	5.76		X
Acetic acid, CH_3COOH	3.10	X	
Citric acid, $C_6H_8O_7$	2.00	X	
pH of water in control mixture	6.70		

Analyzing Model 1 – Dissolving Compounds

17. Did most of the colored compounds dissolve in both water *and* oil, or did most compounds dissolve in one or the other?

    Most compounds dissolved in either oil or water, not both.

18. Which compounds used in this experiment have ionic bonds? Did these dissolve in water or in oil?

    $CuSO_4$, $CoCl_2$, $FeCl_3$ have ionic bonds. They all dissolved in water.

19. Do all of the molecular compounds dissolve in oil? Support your answer with data from the Model 1 Data Table.

    No, some dissolve in oil and some dissolve in water: β-carotene, capsanthin, and lycopene dissolved in oil; riboflavin and betanin dissolved in water.

20. One way to think about which molecular compounds will dissolve in water and which will dissolve in oil is to determine which molecules are able to form hydrogen bonds with the water molecules.

    a. What atoms must be present for a molecule to form a hydrogen bond with water?

        Nitrogen, oxygen, or fluorine, or a hydrogen that is covalently bonded to a nitrogen, oxygen, or fluorine atom.

    Refer to these skeleton structures of four of the Set 1 Compounds:

    Riboflavin

    Betanin

    Lycopene

    Beta-carotene
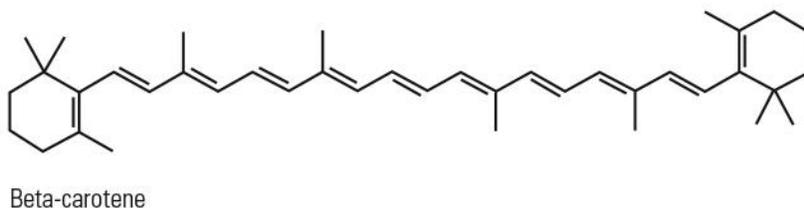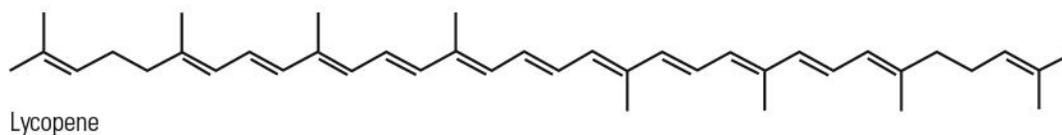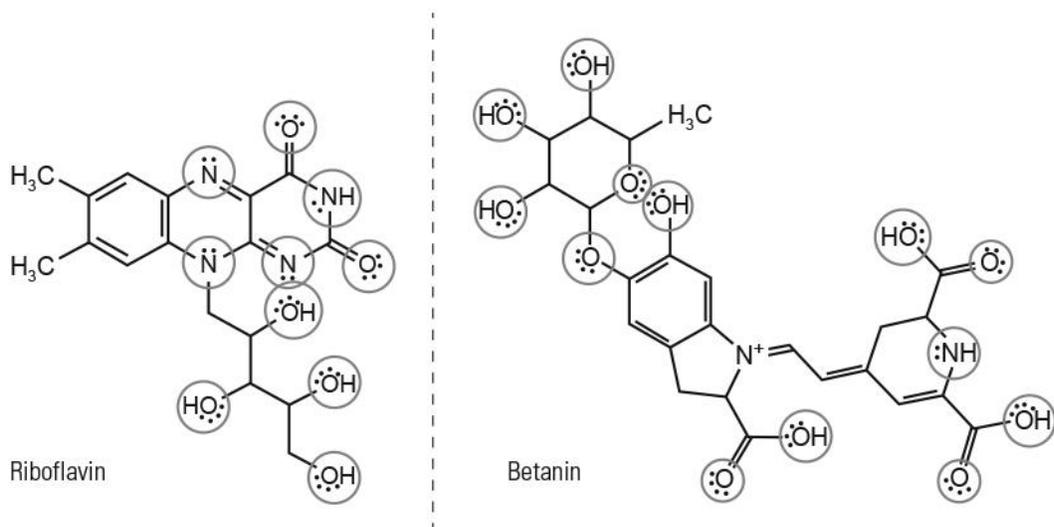
    b. Can riboflavin form a hydrogen bond with water? If so, circle the places on the molecule that could form a hydrogen bond with water.

        Yes, riboflavin can form hydrogen bonds with water. Each of the oxygen and nitrogen atoms in riboflavin, as well as any hydrogen atom covalently bonded to a nitrogen or oxygen atom, can form a hydrogen bond with water.

    c. Can beta-carotene form a hydrogen bond with water? If so, circle the places on the molecule that could form a hydrogen bond with water.

        No, there are no oxygen or nitrogen atoms on the molecule that could form a hydrogen bond.

    d. Are all of the molecules that dissolved in water able to form hydrogen bonds with water?

        Yes.

21. Below is the molecular structure of capsanthin. Does having three or fewer oxygen atoms in a molecule containing 40 carbon atoms provide enough hydrogen bonding to water to make that molecule soluble in water? Justify your answer using your data.
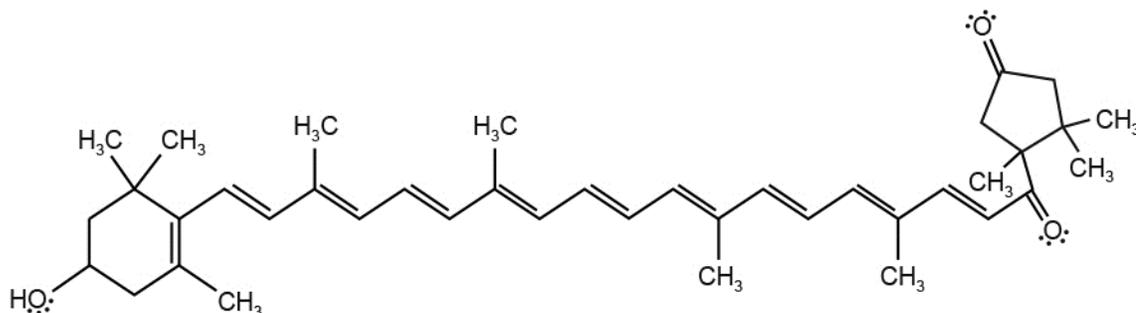
No, it is not enough hydrogen bonding, since the capsanthin dissolved in oil.

22. A second way to think about which compounds will dissolve in water and which will dissolve in oil is to consider which ones are polar and which are nonpolar. Mineral oil is a mixture of molecules that are carbon chains of various lengths (ranging from 18 to 40 carbons). An example of one molecule is shown here:

a. Is this compound polar or nonpolar? Briefly explain your answer.

It is nonpolar because of the long chain of carbon and hydrogen atoms. Carbon and hydrogen have very similar electronegativity and do not form polar bonds.

b. Is water polar or nonpolar? Briefly explain how you know. Include a drawing.

Water is polar. The bent shape of the water molecule and higher electronegativity of oxygen draw electrons to one side of the molecule, making the oxygen side partially negative and the hydrogen side partially positive.
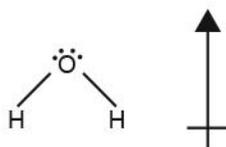
c. Textbooks often use the phrase "like dissolves like" to explain solubility. What they mean by this is that polar compounds dissolve in polar compounds while nonpolar compounds dissolve in nonpolar compounds. Does your data support this statement? Give examples to support your answer.

Yes, most of the data shows that "like dissolves like." Beta-carotene is a nonpolar compound that dissolves in nonpolar oil.

Aspirin is a polar compound that dissolves in water, which is also polar.

23. a. Hexane is shown below. Is hexane a polar or nonpolar compound?
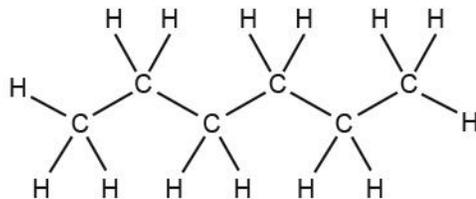
Hexane is nonpolar.

b. Will beta-carotene dissolve in this solvent (hexane)? Briefly explain your answer.

Yes, beta-carotene will dissolve in hexane. Both are nonpolar.

24. Determine if the following compounds will dissolve in oil or water. If the molecule is water soluble, circle the sites where hydrogen bonding with water can occur.

a. Cyanidin (a compound that gives many fruits their red color)
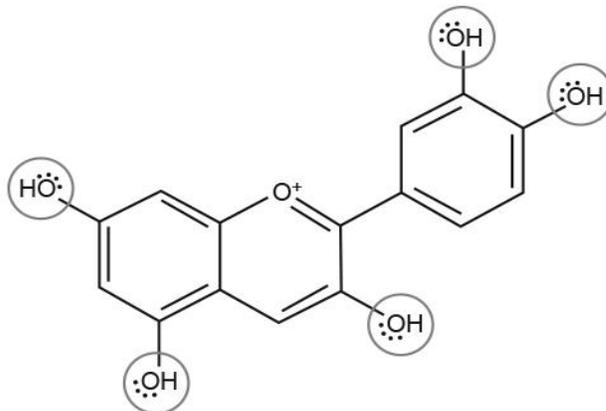
Cyanidin will dissolve in water.

b. Alpha-tocopherol (a form of vitamin E)
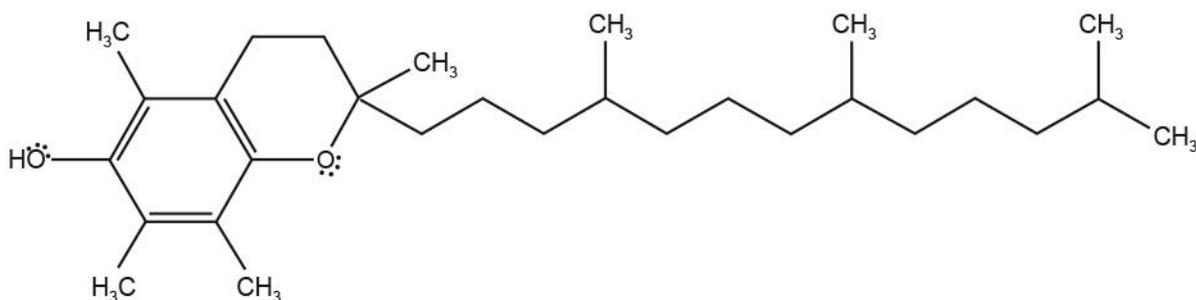
Alpha-tocopherol will dissolve in oil.

25. Suppose lycopene and betanin were both added to an oil–water mixture. Predict where each solute would dissolve best and draw a picture of your prediction.
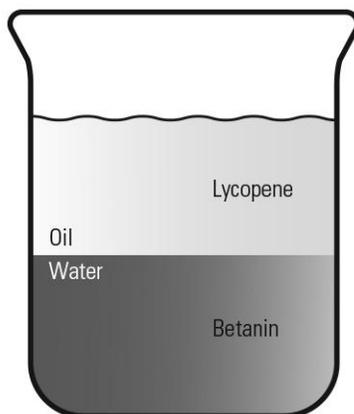
The lycopene, being nonpolar, would dissolve in the oil and the betanin, polar, would dissolve in the water.

26. Barium sulfate, $BaSO_4$, is insoluble in water. Does this characteristic follow the "like dissolves like" guideline? Explain your reasoning.

Barium sulfate is an ionic compound, so it would be considered polar. According to the "like dissolves like" rule, it should be soluble in water, a polar compound. Since it is not soluble in water, however, barium sulfate does not follow the general rule.

MODEL 2

Building Model 2 – Extraction

1. Obtain 10 mL each of the lycopene and betanin solutions (the structures of these molecules are depicted in the Analyzing Model 1 section). Record the color of each solution.

2. Mix the two solutions together in a 100-mL beaker, and then add 20 mL of mineral oil. Stir for 10 seconds then let the mixture sit for two to five minutes. Record your observations.

3. Decant the top layer into a separate beaker. Record your observations in Model 2 – Extraction by either drawing a picture (use colored pencils to record the color) or taking a photo.

Model 2 – Extraction

Observations

Mixture

Lycopene and Betanin

Separation
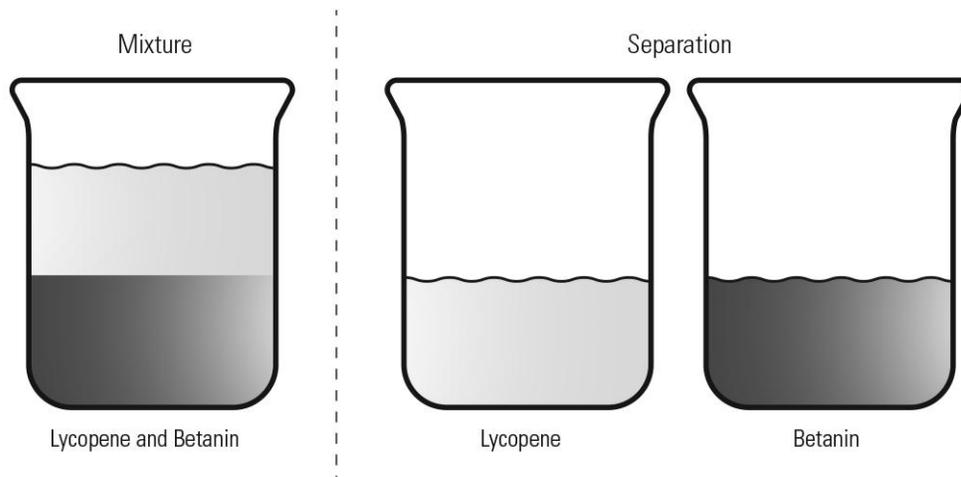
Lycopene

Betanin

Analyzing Model 2 – Extraction

4. Explain how you were able to separate the lycopene and betanin in Model 2.

    Lycopene is a nonpolar compound, so it dissolved in the oil, separating it from the betanin, which is an ionic compound so dissolved in the water.

Connecting to Theory

There are many times in chemical research, manufacturing and industry when mixtures of compounds must be separated. Several techniques are used to achieve separation. Many of these techniques make use of the different solubility of the substances in the mixture. The process you performed in this lab is known as *extraction*—for example, one compound moves into the nonpolar solvent layer, the other stays in the polar solvent layer.

Consider the decaffeination of coffee (extraction of caffeine from coffee beans), which is also accomplished by an extraction method. Coffee beans are soaked in a solvent that dissolves caffeine, but not the other compounds in coffee, such as those that give the coffee its flavor. Over the years, various solvents have been used, including dichloromethane and supercritical CO_2. This process is not 100% efficient; some of the caffeine is not dissolved in the solvent. This is why the coffee is labeled as "decaffeinated" and not "caffeine free."

Chromatography is another commonly-used process that separates the components of a mixture. In this process, a liquid or gas moves over a solid medium (such as paper or silica). Some of the components dissolve better in the mobile phase than others, and so travel farther along the solid medium. Others stick better to the solid. In the end, the components are separated.

Applying Your Knowledge

1. Lycopene, beta-carotene and capsanthin are all converted by your body into vitamin A. Your body is better able to absorb these compounds if the foods they come from (such as tomatoes, carrots, and peppers) are cooked, particularly if they are cooked in a little oil. Why might this be the case?

    These compounds dissolve in the oil and will do so better at higher temperatures. This makes them available for the body to digest.

2. Soap is generally formed from molecules that have long nonpolar "tails" and a "head" that is very soluble in water. Such compounds are called *surfactants*, and an example of one (sodium stearate) is pictured below.
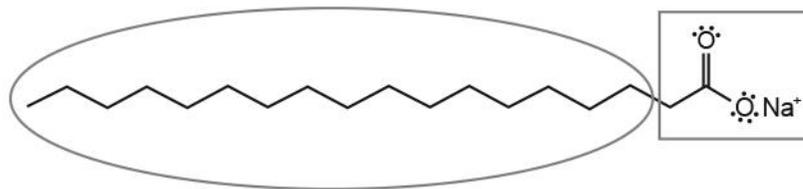
a. Circle the nonpolar region of this molecule

b. Put a box around the polar region of this molecule.

c. What about the structure of the polar region of this molecule will give extremely polar properties?

    The polar region of the molecule is ionic, not just polar.

d. Using what you have learned in this lab, why do you think surfactant molecules are more effective at dissolving oily compounds from dishes than pure water alone?

    The nonpolar region can dissolve the oily compounds on dishes while the polar end can still dissolve in water.

3. Consider what you know about "permanent" ink and ink that can be washed off in water. How are the compounds used in those inks different?

    The water soluble ink molecules likely contain many oxygen atoms, making them polar and allowing them to form hydrogen bonds with water and be washed away. The permanent ink is probably made mostly of carbon and hydrogen atoms, so it is nonpolar.

Teacher Tips

Tip 1 – Preparing the lab

This lab requires a substantial amount of preparation. To make the preparation go smoothly, begin a day or two prior to carrying out the lab. This reduces some of the agitation and filtering. There is no strict rule on how long solutions must sit before straining or separating the layers. You could prepare them a week in advance, or right before the lab, if necessary.

Tip 2 – Rinsing pH meters and cleaning up

Students are directed to measure the pH of their water samples after pipetting the water layer from the beaker with the oil and water. This prevents the pH sensor from being submerged in oil. However, it will inevitably come in contact with some oil, so students are directed to wash them with both soapy water and distilled water. Make sure to supply them with a dilute, mild detergent.

Provide students with a mild detergent solution for rinsing their beakers and lab counters. Detergents like Dawn® work better than most lab soaps.

Tip 3 − Paper chromatography

You may wish to have your students execute a paper or thin-layer chromatography experiment as a follow-up to this experiment. The same solvent–solute interactions come into play with the added complication of the solute–solid phase interaction. However, students will be better prepared for that discussion, having completed this lab activity.

Tip 4 − Separatory funnels

If separatory funnels are available, you may wish to use them in Model 2.

6. SOLUBILITY

Initial Question

Most ionic compounds are considered to be soluble or slightly soluble in water. Even compounds considered insoluble will dissolve to some small extent. This small extent can become very important when the dissolved substance is poisonous like lead, thallium, or cadmium. Over time, tiny amounts of these heavy metals can build up in your body and cause severe health problems. By knowing the amount of a dissolved ion in a solution, we can determine any potential health risks.

How can you determine the amount of dissolved ions in a solution?

Learning Objectives[*]

Students determine the saturation concentration of a compound and the mass of dissolved solute.

LO 2.15 / The student is able to explain observations regarding the solubility of ionic solids and molecules in water and other solvents on the basis of particle views that include intermolecular attractions and entropic effects.

LO 2.19 / The student can create visual representations of ionic substances that connect the microscopic structure to macroscopic properties, and/or use representations to connect the microscopic structure to macroscopic properties (e.g., boiling point, solubility, hardness, brittleness, low volatility, lack of malleability, ductility, or conductivity).

LO 6.21 / The student can predict the solubility of a salt, or rank the solubility of salts, given the relevant K_{sp} values.

SP 4.3 / The student can *collect data* to answer a particular scientific question.

Time Requirement

Preparation time: 20 minutes / Lab activity: 60 minutes

Materials and Equipment

Model 1

- Data collection system
- Conductivity sensor[1]
- Beakers (3), 150-mL
- Balance (1 per class)
- Stirring rod
- Graduated cylinder, 100-mL

- Unknown A, solid, 1.0 g[2]
- Unknown B, solid, 1.0 g[3]
- Unknown C, solid, 1.0 g[4]
- Distilled water, 300 mL
- Wash bottle with distilled deionized water

[1]Included with PASCO Advanced Chemistry Sensor.
[2]Unknown A is solid glucose ($C_6H_{12}O_6$).
[3]Unknown B is solid potassium bitartrate ($KHC_4H_4O_6$), also known as potassium hydrogen tartrate (KHT), or cream of tartar.
[4]Unknown C is solid sodium sulfate (Na_2SO_4).

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Model 2

- Data collection system
- Conductivity sensor[1]
- Magnetic stir bar
- Stir plate
- Ring stand
- Graduated cylinder, 100-mL

- Balance (1 per class)
- Beaker, 150-mL
- Clamp
- Potassium bitartrate ($KHC_4H_4O_6$), solid, 4.2 g
- Distilled water, 100 mL

[1]Included with PASCO Advanced Chemistry Sensor.

Model 3

- Erlenmeyer flask, 125-mL
- Mohr pipet, 25-mL
- Pipet bulb
- Beaker (2), 150-mL
- Buret
- Buret clamp
- Funnel

- Quantitative filter paper
- Magnetic stir bar
- Stir plate
- Phenolphthalein, 3 drops
- 0.10 M Sodium hydroxide (NaOH), 80 mL
- Distilled water, 20 mL

Prerequisites

Students should be familiar with the following concepts:

- Molarity

- Ionic and covalent bonding

- Conductivity

- Solution equilibria

- Titration

Lab Preparation

These are the materials and equipment to set up prior to the lab:

Applying Your Knowledge

0.10 M Sodium hydroxide: Prepare 1000 mL of 0.10 M sodium hydroxide (NaOH) by placing 3.999 g of solid NaOH in a 1000-mL volumetric flask 1/3 full of distilled water. Stir it well. When the solid has completely dissolved, fill the flask to the line with distilled water.

Safety

Add these important safety precautions to your normal laboratory procedures:

- In addition to goggles and an apron, wear gloves.

Getting Your Brain in Gear

1. Why would the conductivity of a solution change when solute is added?

   There are more dissolved ions in the solution.

2. Based on conductivity, how can you distinguish between soluble ionic and molecular solutes when they are dissolved in water?

   Molecular solutes will dissolve but do not change the conductivity.

   Ionic solutes will dissolve and change the conductivity.

3. Consider the three beakers below. Label the solutions either saturated or unsaturated. Explain your reasoning.

5.0 M NaCl	6.2 M NaCl	6.2 M NaCl
Unsaturated	Saturated	Saturated

□ Na⁺ (aq)
▷ Cl⁻ (aq)
▷□ NaCl (s)
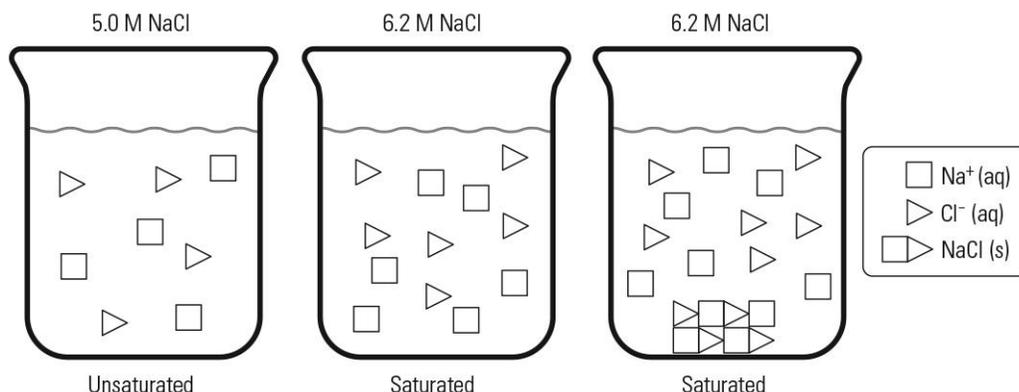
   The beaker on the right is saturated because there is solid solute at the bottom. Since the concentration of solute in the middle beaker is equal to that of the beaker on the right, it is also saturated; the solvent can hold no more dissolved solid. The beaker on the left is unsaturated because the concentration of solute in that beaker is less than in the middle beaker.

4. Bitartrate is a polyatomic ion with the formula $HC_4H_4O_6^-$. In a saturated solution of potassium bitartrate, the following equilibrium reaction occurs:

$$KHC_4H_4O_6(s) \rightleftharpoons K^+(aq) + HC_4H_4O_6^-(aq)$$
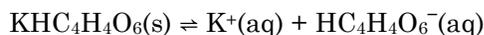
   Describe the chemical processes during the forward and reverse reactions.

   During the forward reaction, the compound dissolves to form K^+ and $HC_4H_4O_6^-$. During the reverse reaction, the K^+ and $HC_4H_4O_6^-$ form the solid compound.

MODEL 1

Building Model 1 – Saturated or Unsaturated?

1. Obtain three 150-mL beakers and label them "A," "B," and "C."

2. Pour 100 mL of distilled water into each of the beakers.

3. Connect the conductivity sensor to the data collection system.

4. Insert the conductivity sensor into the water in Beaker A.

    NOTE: Make sure the small hole on the side of the conductivity probe is submerged. Gently tap the conductivity probe to remove any trapped bubbles.

5. Start data collection. Record the conductivity in the Model 1 Data Table.

6. Measure and add 1.0 g of unknown solid A to the beaker.

7. Stir the solution with a glass stirring rod and then record the conductivity and appearance on the Model 1 Data Table.

8. Make a particulate drawing for the unknown in solution in Model 1.

9. Rinse the conductivity probe with distilled deionized water and then repeat the previous steps with unknowns B and C in their respective beakers.

Model 1 – Saturated or Unsaturated?
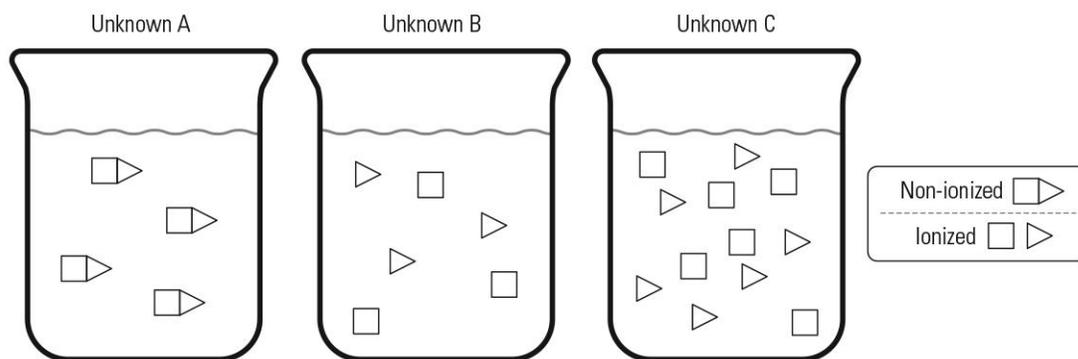
Table 1: Model 1 Data Table—Identifying a saturated solution

Unknown	Appearance	Conductivity (µS/cm)	
		Water	Water Plus Unknown
Unknown A	clear	~50	~50
Unknown B	cloudy	~50	~3300
Unknown C	clear	~60	~11000

Analyzing Model 1 – Saturated or Unsaturated?

10. Which of the solutions would you describe as unsaturated? Explain your reasoning.

    The solutions with unknowns A and C—both of these solutions are clear.

11. Which of the solutions would you describe as saturated? Explain your reasoning.

    The solution with unknown B—the solution is cloudy.

12. Which of the unknowns would you describe as ionic? As covalent? Explain your reasoning for each.

    Unknown B and unknown C are ionic, because when dissolved in water, the conductivity of their solutions is greater than the conductivity of water. Unknown A is covalent because when dissolved in water, its conductivity is the same as the conductivity of water.

13. How could you experimentally verify your answers above?

    Add more solute. If the solution is saturated, no more will dissolve. If unsaturated, more will dissolve.

    The solutions containing unknown B and unknown C will increase in conductivity when they are added to the solution while the solution is unsaturated. The conductivity will remains steady as solute is added once the solutions are saturated.

    For the solution with unknown A, the conductivity should not increase as more solute is added.

14. If you are going to use conductivity to help determine the saturation of a solution, what can you say about the substance you use for this study?

    The substance must be an ionic compound.

MODEL 2

Building Model 2 – Reaching Saturation

1. Connect the conductivity sensor to the data collection system.

2. Pour 100.0 mL of distilled water into a 150-mL beaker.

3. Add a stir bar to the beaker and place the beaker on a magnetic stirrer, placed on the base of the ring stand.

4. Use the ring stand and clamp to hold the conductivity sensor immersed in the water in the beaker and then turn on the magnetic stirrer.

   NOTE: Make sure the small hole on the side of the conductivity sensor is submerged. Gently tap the conductivity probe to remove any trapped bubbles.

5. Start data collection. Record the conductivity and the appearance of the solution in the Model 1 Data Table.

6. While constantly stirring, add 0.2 g of potassium bitartrate to the beaker.

7. After 4 minutes, record the conductivity and appearance in the Model 2 Data Table.

8. With constant stirring, add an additional 0.2 g of potassium bitartrate to the beaker. After 4 minutes, record the conductivity and appearance of the solution.

9. Continue this process of adding 0.2 g of potassium bitartrate to the beaker and stirring for 4 minutes until 1.2 g have been added.

10. Make particulate level drawings of the solutions before potassium bitartrate is added, after 0.6 g are added, and after 1.2 g are added.

Before potassium
bitartrate is added

0.6 g potassium
bitartrate added

1.2 g potassium
bitartrate added

Non-ionized

Ionized
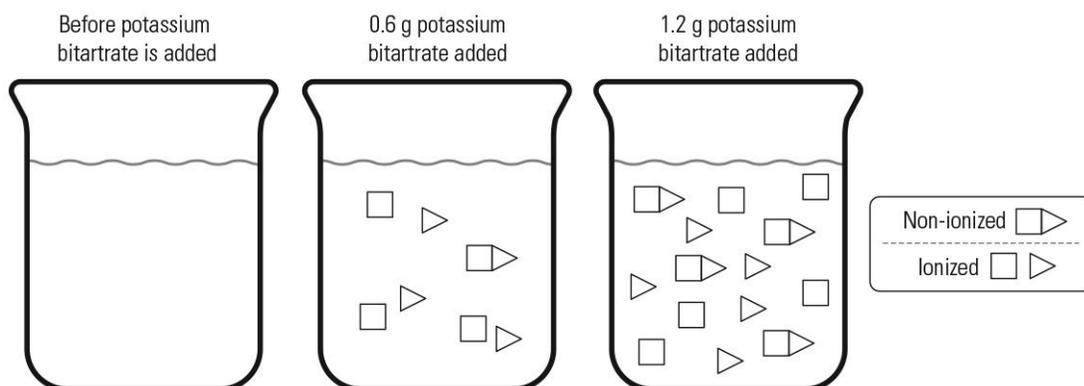
11. Sketch a graph of conductivity on the *y*-axis and total mass of potassium bitartrate added on the *x*-axis.

12. Do not discard the contents in your beaker. Save the solution for Model 3.

Model 2 – Reaching Saturation

Table 2: Model 2 Data Table – Detecting the saturation point

Trial	Total Potassium Bitartrate Added (g)	Conductivity	Appearance	Saturated or Unsaturated?
1	0.0	125	Clear	Unsaturated
2	0.2	1087	Clear	Unsaturated
3	0.4	1700	Clear	Unsaturated
4	0.6	2700	Slightly cloudy	Unsaturated
5	0.8	3300	Cloudy	Saturated
6	1.0	3400	Cloudy	Saturated
7	1.2	3400	Cloudy	Saturated

Conductivity vs mass of $KHC_4H_4O_6$ (g)

Conductivity (10x probe) (µS/cm)

Mass of $KHC_4H_4O_6$ (g)
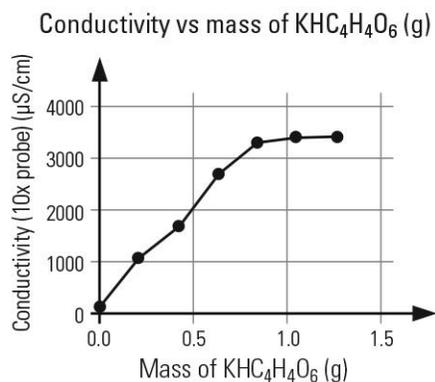
Analyzing Model 2 – Reaching Saturation

13. In the Model 2 Data Table, describe the solution after each trial as either saturated or unsaturated.

    Because the solution is slightly cloudy, students may describe Trial 4 as saturated, but because the conductivity is still increasing, it is unsaturated.

14. What is the approximate mass of $KHC_4H_4O_6$ required to saturate 100 mL of water? Explain your reasoning using at least two instances of data-based evidence.

    Approximately 0.8 grams of $KHC_4H_4O_6$ in 100 mL of water will saturate the solution. The water began turning cloudy after 0.6 g of $KHC_4H_4O_6$ had been added but the conductivity continued to increase, indicating more of the substance was dissolving in the water. The conductivity stopped increasing after approximately 0.8 g had been added.

MODEL 3

Building Model 3 – Quantifying Solubility

1. Use the following steps to remove any solids from the solution you saved from Model 2.

   NOTE: Do not add any water to the filtrate.

   a. Assemble a filtration setup as in the diagram shown at the right, using a 125-mL Erlenmeyer flask, filter paper, and a funnel.

   b. Fold the filter paper and place it into the funnel.

   c. Slowly pour the contents of the beaker into the funnel. Do not over fill the filter paper.

   d. Continue until all of the filtrate has moved through the filter paper into the flask.
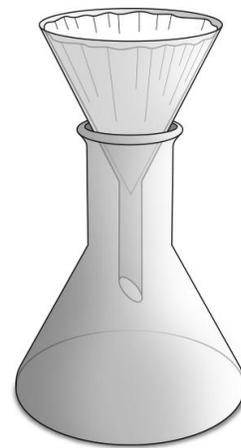
❷ 2. Is the filtered solution saturated or unsaturated?

   As long as no water was added, the solution is still saturated.

3. Insert the magnetic stir bar into a clean, dry, 150-mL beaker. Then, using a Mohr pipet, deliver 25 mL of the filtered potassium bitartrate solution from the Erlenmeyer flask into the beaker. Save the rest of the solution for a second trial.

4. Add approximately three drops of phenolphthalein indicator to the potassium bitartrate solution in the beaker.

5. Use a ring stand to set up a buret, as shown.

Stopcock

Magnetic stir bar
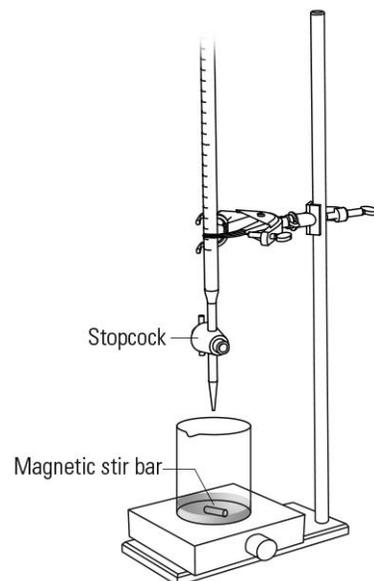
6. Rinse the buret:

    a. Open the stopcock and then place a waste beaker under the buret.

    b. Rinse the buret three times with small amounts of distilled water. This will remove any residue.

    c. Rinse the buret three times with small amounts of 0.10 M NaOH. This will push out any water or other impurities.

7. Close the stopcock. Replace the waste beaker with the 150-mL beaker that contains the 25 mL of potassium bitartrate and phenolphthalein. Dispose of the waste according to your teacher's instructions.

8. Fill the buret with 0.10 M NaOH. Record the initial volume in the Model 3 Data Table.

9. Turn on the magnetic stirrer. Then open the stopcock to achieve a steady drip of approximately one drop per second. Add the 0.10 M NaOH until you get a permanent, faint pink color in the solution, and then close the stopcock.

10. Record the final volume of sodium hydroxide in the Model 3 Data Table.

11. Repeat the previous steps for a second trial using another 25-mL sample of the $KHC_4H_4O_6$ solution. Calculate the volume of titrant added for each trial and determine the average volume.

Model 3 – Quantifying Solubility

Table 3: Model 3 Data Table—Using titration to determine solubility

Parameters	Trial 1	Trial 2	Average
Volume of KHC4H4O6 solution (mL)	25.00	25.00	
Concentration of NaOH used (M)	0.10	0.10	
Initial titrant volume (mL)	0.00	10.5	
Final titrant volume (mL)	10.5	21.0	
Volume of titrant added to reach the endpoint (mL)	10.5	10.5	10.5

Analyzing Model 3 – Quantifying Solubility

12. Bitartrate is a weak acid and sodium hydroxide reacts with it according to the following net ionic reaction:

$$OH^-(aq) + HC_4H_4O_6^-(aq) \rightleftharpoons H_2O(l) + C_4H_4O_6^{2-}(aq)$$
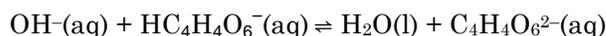
    a. Calculate the average number of moles of OH^- used in the titrations.
       0.0105 L × 0.10 M OH⁻ = 0.00105 mol OH⁻

    b. Calculate the average number of moles of $HC_4H_4O_6^-$ in the 25.0-mL sample of the solution.
       Because there is a 1:1 stoichiometric ratio, there are 0.00105 moles of HC4H4O6⁻.

    c. Calculate the average molarity of the $HC_4H_4O_6^-$ in the solution.
       0.00105 mol HC4H4O6⁻ /0.025 L sample = 0.042 M

d. Calculate the average mass of the $KHC_4H_4O_6$ dissolved in 100 mL of water.

0.042 mol/1 L solution = 0.042 mol/1000 mL, so there are 0.0042 mol/100 mL solution

0.0042 mol × 188.18 g/mol = 0.79 g $KHC_4H_4O_6$

13. Compare this mass of $KHC_4H_4O_6$ to the approximated mass in Model 2.

Students should find that they are similar in value. In Model 2 it was estimated that 0.8 grams of $KHC_4H_4O_6$ in 100 mL of water will saturate the solution. The calculation based on the measured mass shows that 0.79 g will dissolve.

Connecting to Theory

The ability of a compound to dissolve in a solvent is its solubility. The solubility of an ionic compound refers to the maximum amount of solute that can dissolve in a given amount of solvent at standard temperature and pressure. The solution of an ionic compound containing the maximum amount of solute is known as a saturated solution and is in a state of equilibrium between dissolved and undissolved solute.

The solubility product constant, K_{sp}, is a temperature-dependent constant that refers to this state. If a salt, M_xA_y, dissociates into cations $[M^{m+}]$ and anions $[A^{a-}]$ the expression for the solubility product will be

$$K_{sp} = [M^{m+}]^x[A^{a-}]^y$$

where "[ ]" indicates the molar concentration of the ion in solution.

For example, the equation below describes the equilibrium of a saturated solution of calcium carbonate in water:

$$CaCO_3(s) \rightleftharpoons Ca^{2+}(aq) + CO_3^{2-}(aq)$$
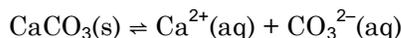
Calcium carbonate dissolves in the solution in the forward reaction and at the same time calcium carbonate precipitates from the solution in the reverse reaction. When both reactions occur at the same rate, a state of equilibrium is established.

The K_{sp} expression for calcium carbonate would be:

$$K_{sp} = [Ca^{2+}][CO_3^{2-}]$$

Applying Your Knowledge – Determining Solubility Equilibrium

1. Write the K_{sp} expression for potassium bitartrate using the following equilibrium reaction:

$$KHC_4H_4O_6 (s) \rightleftharpoons K^+ (aq) + HC_4H_4O_6^- (aq)$$
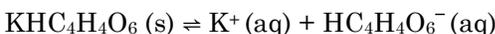
$K_{sp} = [K^+] [HC_4H_4O_6^-]$

2. Based on the formula of potassium bitartrate and the average molarity at saturation of bitartrate from Model 3, what are the molarities of potassium ions and the bitartrate ions in a saturated solution?

The molarity determined at saturation is 0.042 M.

$KHC_4H_4O_6(s) \rightleftharpoons K^+(aq) + HC_4H_4O_6^-(aq)$
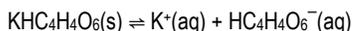
$[K^+] = [HC_4H_4O_6^-] = 0.042$ M

a. Calculate the value of K_{sp} for potassium bitartrate.

$K_{sp} = [K^+] [HC_4H_4O_6^-] = 0.042^2 = 1.8 \times 10^{-3}$

3. Copper(II) tartrate, $CuC_4H_4O_6$, dissolves in water according to the following equation

$$CuC_4H_4O_6(s) \rightleftharpoons Cu^{2+}(aq) + C_4H_4O_6{}^{2-}(aq)$$
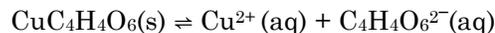
The K_{sp} of copper(II) tartrate is 4.0×10^{-4}.

a. What is the K_{sp} expression of copper(II) tartrate?

$K_{sp} = [Cu^{2+}][C_4H_4O_6{}^{2-}]$

b. What is the molarity of a saturated solution of copper(II) tartrate?

$K_{sp} = [Cu^{2+}][C_4H_4O_6{}^{2-}] = 4.0 \times 10^{-4}$

Therefore, since $[Cu^{2+}] = [C_4H_4O_6{}^{2-}]$, the molarity is $\sqrt{4.0 \times 10^{-4}}$, or 2.0×10^{-2} M .

c. If 0.200 grams of copper(II) tartrate are added to 100 g of water, is the solution saturated?

$$\frac{0.200 \text{ g}}{0.100 \text{ L}} \times \frac{1 \text{ mol}}{211.63 \text{ g copper(II) tartrate}} = 9.45 \times 10^{-3} \text{M } CuC_4H_4O_6$$

This concentration of copper(II) tartrate is less than the concentration required to reach saturation, 2.0×10^{-2} M, so this is an unsaturated solution.

Teacher Tips

Tip 1 – Source of potassium bitartrate

You can use cream of tartar, another name for potassium bitartrate, which can be purchased at a grocery store.

7. EMPIRICAL FORMULA

Initial Question

A major emphasis of laboratory work for a chemist is determining the composition of a compound. There are many tools, such as chromatographic separation and spectroscopy, that aid the chemist in determining chemical composition. By keeping track of mass and breaking a compound into its component pieces, the pieces can be measured and the composition determined.

How do you discover the formula for an unknown substance?

Learning Objectives[*]

The student is able to use stoichiometric calculations to analyze the results of a reaction carried out in the laboratory.

LO 3.6 / The student is able to use data from synthesis or decomposition of a compound to confirm the conservation of matter and the law of definite proportions.

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

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

Time Requirement

Preparation time: 20 minutes / Lab activity: 90 minutes

Materials and Equipment

Model 1
- Hot plate, 1 per group, or an oven for the class
- Crucible and cover
- Crucible tongs

- Copper hydrate unknown, 1.0–1.5 g[1]
- Balance (1–2 per class)

Model 2
- Data collection system
- Colorimeter sensor
- Sensor extension cable[1]
- Cuvette[1]
- Graduated cylinder, 25-mL

- Volumetric flask, 100-mL
- Copper hydrate unknown, 1.0–1.5 g[2]
- 0.10 M Copper chloride ($CuCl_2 \cdot 2H_2O$), 60 mL[3]
- Distilled water, 25 mL

[1]Included with PASCO Colorimeter

[1]Use copper chloride dihydrate ($CuCl_2 \cdot 2H_2O$) as the copper hydrate unknown for both Model 1 and Model 2. Refer to the Lab Preparation section.

[2]To prepare 0.10 M $CuCl_2$, refer to the Lab Preparation section

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Prerequisites

Students should be familiar with the following concepts:

- Percent by mass
- Heating with a crucible and cover
- Law of Definite Proportions

Lab Preparation

These are the materials and equipment to set up prior to the lab:

Model 1 and Model 2

NOTE: Assign student groups a specific mass of hydrate that they will use in both Model 1 and Model 2 to ensure a good distribution of data. In this lab, it is not ideal for all groups to work with the same mass. Students should see that even though different amounts of samples were used, the resulting ratio of components was the same.

1. **Unknown Copper(II) chloride:** Provide an unlabeled container for the students' copper hydrate unknown, $CuCl_2 \cdot 2H_2O$.

Model 2

2. **0.1M Copper(II) chloride:** Prepare 1 L of 0.10 M copper(II) chloride dihydrate ($CuCl_2 \cdot 2H_2O$), by filling a 1000 mL volumetric flask 1/3 full of distilled water. Add 17.048 g of copper(II) chloride dihydrate to the flask and swirl to dissolve it. Fill the flask to the mark with distilled water. Students will dilute this solution to prepare standard solutions for applying Beer's Law.

Safety

Add these important safety precautions to your normal laboratory procedures:

- Do not look into a hot crucible. Hot material may be ejected.
- Do not touch chemicals with your hands.

Getting Your Brain in Gear

1. In this lab, you will be heating a hydrate to remove the water. Label the appropriate molecules in the before-heating and after-heating diagrams below with "Hydrate," "Anhydrous salt," and "Water."

Before heating   After heating
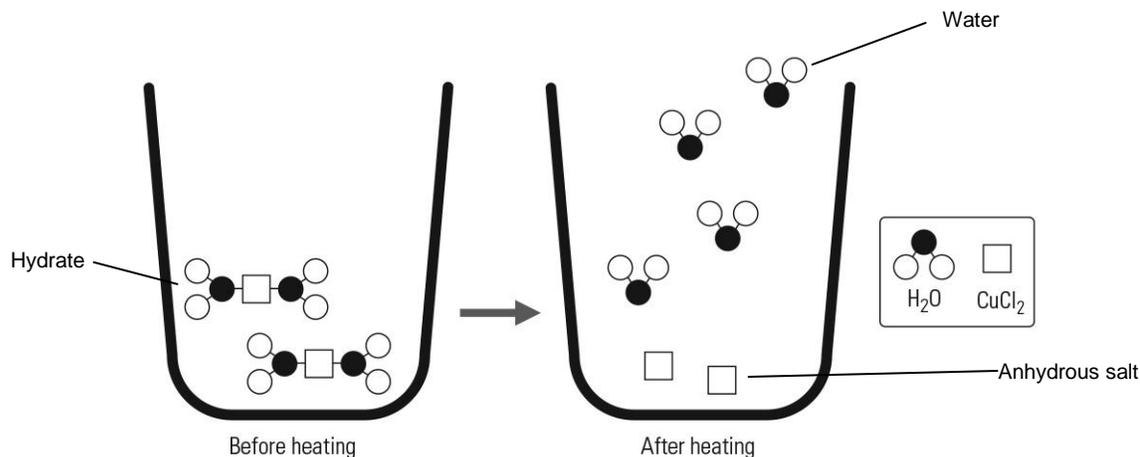
2. Write a mathematical equation that would show the relationship between the mass of the hydrate, the mass of water lost, and the mass of the anhydrous salt.

    Mass of hydrate = Mass of water lost + Mass of anhydrous salt

3. There are two possible ionic compounds that can be formed by copper and chlorine. Write their chemical formulas.

    $CuCl$ and $CuCl_2$

4. Recall that copper ions have a blue to green color in solution. Propose a lab technique that could be used to determine the concentration of copper ion in a solution prepared with your hydrate sample.

    Spectroscopy could be used to find the concentration of copper ion in a solution of the hydrate sample.

MODEL 1

Building Model 1 – Percentage of Water

1. Clean and dry a small ceramic crucible and cover.

2. Measure the mass of the crucible and cover. Record this in the Model 1 Data Table.

3. Measure between 1.0 and 1.5 grams of the unknown in the crucible (the cover should be on the balance, as well). Record the total mass of the sample, crucible, and cover in the Model 1 Data Table.

❷ 4. In this lab procedure, you obtain the mass of the unknown in the crucible. Explain why this method is preferred over finding the mass of the unknown in a weighing container and then pouring the sample into the crucible.

    This procedure limits the amount of solid lost during the transfer from the balance to the crucible and cover.

5. Set up a hot plate to heat the uncovered crucible. Use a medium setting.

    NOTE: Heating the hydrate too hot (>300 °C) will result in the production of poisonous chlorine gas.

6. As water is released from the sample, the color will change from blue to brown. Use crucible tongs to gently shake the crucible occasionally to expose the blue hydrate in the middle. Continue heating until the blue color is gone; this will take ten to fifteen minutes. Work on the problem below while you wait.

❷ 7. In Model 2 you will use a spectrophotometric technique to determine the percentage of copper ion in your sample. To do this, you will need standard solutions of 0.10 M, 0.08 M, 0.06 M and 0.04 M copper ion. You will be given a stock solution of 0.10 M copper ion. Perform the calculations and write a procedure for how you will make at least 20.0 mL of each of the standard solutions.

    0.10 M   Use the stock solution "as is"

    0.08 M   0.10 M (*x*) = 0.08 M (20.0 mL)   *x* = 16.0 mL
                  Add 4.0 mL of distilled water to 16.0 mL of 0.10 M stock solution.

    0.06 M   0.10 M (*x*) = 0.06 M (20.0 mL)   *x* = 12.0 mL
                  Add 8.0 mL of distilled water to 12.0 mL of 0.10 M stock solution.

    0.04 M   0.10 M (*x*) = 0.04 M (20.0 mL)   *x* = 8.0 mL
                  Add 12.0 mL of distilled water to 8.0 mL of 0.10 M stock solution.

8. Once all the crystals are brown, remove the crucible from the hot plate with crucible tongs. Let the sample cool with the cover in place. After cooling for five minutes, find and record the total mass of the sample, crucible, and cover.

    NOTE: You cannot measure the mass of a hot object on the balance.

❷ 9. Why is it necessary to heat the sample with the cover removed?

    The water needs to be able to escape as steam from the crucible.

❷ 10. Why is it necessary to let the substance dry with the cover on?

Leaving the cover on when the substance dries prevents rehydration from the air.

11. To ensure that all the water has been removed, reheat the crucible with the unknown for five minutes (uncovered). Let the sample cool on the desk (covered) and then obtain the mass as you did previously. Continue to heat in five-minute intervals until all of the water has been removed from the hydrate sample.

❷ 12. How will you know if you have heated the hydrate sufficiently to remove all of the water?

The mass of the hydrate will no longer change when heated.

13. Transfer the brown anhydrous sample from your crucible to the solid waste jar in the hood. Rinse and dry the crucible.

Model 1 – Percentage of Water

Table 1: Model 1 Data Table—Determine the percentage of water in the hydrate

Parameters	Mass (g)
Crucible and cover	23.31
Hydrate sample, crucible and cover	24.73
After 1st heating	24.44
After 2nd heating	24.42
After 3rd heating (if necessary)	

Analyzing Model 1 – Percentage of Water

14. Calculate the mass of water lost from the hydrate.

24.73 g – 24.42 g = 0.31 g water lost from the hydrate

15. Calculate the percentage of water in the original sample.

Mass of sample = 24.73 g – 23.31 g = 1.42 g

(0.31 g / 1.42 g) × 100 = 21.8 %

16. Complete Table 2 using data from your classmates to compare different sized samples of hydrate. Compute the average percentage of water in the sample.

Table 2: Compare class results for the percentage of water in the hydrate

Mass of Hydrate Sample (g)	Mass of Water Lost (g)	Percentage of Water in Hydrate (%)
1.42	0.31	21.8
1.02	0.20	19.6
0.97	0.20	20.6

Average percentage of water in the hydrate: 20.66%

17. Consider the class data above.

    a. How does the mass of water lost relate to the mass of the hydrate sample?

       As the mass of the hydrate increases, the mass of water lost also increases.

    b. How does the percentage of water lost relate to the mass of the hydrate sample?

       The percentage of water lost is similar for all samples.

18. Explain how the class data above supports the Law of Definite Proportions.

    A hydrate is a compound, so it has a specific chemical formula. Every sample of that compound has the same ratio of water molecules to salt.

MODEL 2

Building Model 2 – Moles of Copper

1. Add a 1.0 to 1.5 gram sample of hydrate to a 100.0 mL volumetric flask and fill it to the mark with distilled water.

   Mass of copper hydrate sample: 1.21 g

2. For obtaining a graph exhibiting Beer's Law, prepare the four copper ion standards (0.10 M, 0.08 M, 0.06 M, 0.04 M) as you described in the Building Model 1 section.

❷ 3. What color is the copper ion when dissolved in water?

   Blue-green

❷ 4. Which wavelength of light do you anticipate will give the highest absorbance reading on the colorimeter?

   A wavelength of 660 nm will give the highest absorbance reading.

❷ 5. What color of light does that wavelength correspond to?

   Red

❷ 6. You will be using the linear regression of the line to determine the number of moles of copper ion present in your sample. Would it be better to fit the absorbance or transmittance data? Explain your reasoning.

   It would be better to fit the absorbance data because that data should create a straight line.

7. Calibrate the colorimeter.

8. Record the absorbance in the Model 2 Data Table for each standard solution, sketch or attach a copy of your graph of concentration versus absorbance, and use the linear regression of the line to acquire and record the equation for the line.

9. Record the absorbance in the Model 2 Data Table for your unknown hydrate solution.

Model 2 – Moles of Copper

Table 3: Model 2 Data Table—Using a standard curve to determine the concentration of the unknown

Copper Ion Concentration	Absorbance	Graph
0.10 M	0.491	
0.08 M	0.371	Concentration vs Absorbance
0.06 M	0.256	
0.04 M	0.181	
Unknown	0.359	$y = 0.1894x + 0.0085$

Analyzing Model 2 – Moles of Copper

10. Use the equation obtained from the absorbance data from the copper ion standards to find the concentration of copper ion in the solution made with your hydrate sample.

    From the graph: $y = 0.1894x + 0.0085$

    $y = 0.1894(0.359) + 0.0085 = 0.076495$ M copper ion

11. Determine the number of moles of copper in the unknown.

    The sample was prepared in a 100.0 mL flask.

    $$\frac{0.0764946 \text{ mol copper}}{L} \times \frac{0.1000 \text{ L}}{1} = 0.0076495 \text{ mol copper}$$

12. Calculate the number of moles of water in the unknown using the percentage of water determined in Model 1.

    The average percentage of water in the unknown is 20.66%, so the number of moles of water is:

    1.2118 g hydrate sample $\times 0.2066 = 0.2504$ g H_2O

    $$\frac{0.2504 \text{ g } H_2O}{1} \times \frac{1 \text{ mole}}{18.01532 \text{ g } H_2O} = 1.390 \times 10^{-2} \text{moles } H_2O$$

13. Calculate the ratio of the number of moles of water to that of copper in your hydrate. Reduce the ratio to whole numbers.

    $$\frac{1.390 \times 10^{-2} \text{mol } H_2O}{0.0076495 \text{ mol copper}} = \frac{1.817 \text{ mol } H_2O}{\text{mol copper}} \approx \frac{2 \text{ mol } H_2O}{\text{mol copper}}$$

14. Complete Table 4 using data from your classmates to compare the results when using different sized samples of hydrate.

Table 4: Compare class results for the ratio of the number of moles of water to those of copper

Mass of Hydrate Sample (g)	Moles of Water (mol)	Moles of Copper Ion (mol)	Moles H_2O : Moles Cu
1.2118	0.0138969	0.007649	2:1
1.4671	0.0168247	0.008848	2:1
1.2212	0.0140047	0.007536	2:1
1.0048	0.0115231	0.006418	2:1
1.1012	0.0126286	0.006892	2:1

15. Consider the class data above. How does the ratio of moles of water to moles of copper relate to the mass of the hydrate sample?

The ratio always rounds to a 2:1 ratio, regardless of the mass of the hydrate sample.

16. Explain how the class data above supports the Law of Definite Proportions.

There is a constant or "definite" proportion of water to copper ions.

17. Determine the mass of chlorine present in your hydrate sample. (Hint: The hydrate contains only copper atoms, chlorine atoms and water molecules.)

By calculating the mass of copper and then subtracting that mass and the mass of water (calculated earlier) from the mass of the sample, the mass of the chlorine can be determined:

$$\frac{0.0076494 \text{ mol copper}}{1} \times \frac{63.546 \text{ g copper}}{1 \text{ mol copper}} = 0.486089 \text{ g copper}$$

1.2118 g hydrate sample $-$ 0.250358 g H_2O $-$ 0.486089 g copper $=$ 0.475353 g chlorine

18. Calculate the ratio of the number of moles of copper to the number of moles of chlorine in your hydrate. Reduce the ratio to whole numbers.

$$\frac{0.475353 \text{ g chlorine}}{1} \times \frac{1 \text{ mol of chlorine}}{35.453 \text{ g chlorine}} = 1.34080 \times 10^{-2} \text{mol chlorine}$$

$$\frac{1.34080 \times 10^{-2} \text{mol chlorine}}{0.0076494 \text{ mol copper}} = \frac{1.7528 \text{ mol chlorine}}{\text{mol copper}} \approx \frac{2 \text{ mol chlorine}}{\text{mol copper}}$$

19. The formula for your hydrate has the form $Cu_xCl_y \cdot zH_2O$. Determine x, y and z in the formula from your answers above and identify your hydrate sample.

Based on the previous calculations, $x = 1$, $y = 2$, and $z = 2$ so the formula of the hydrate is $CuCl_2 \cdot 2H_2O$.

Connecting to Theory

John Dalton was an Englishman, a teacher, and an exceptional theoretical chemist. He developed and wrote many postulates of the modern atomic theory at the turn of the 19th century (circa 1803). He was influenced by the experiments of two Frenchmen, Antoine Lavoisier and Joseph Louis Proust.

A fundamental component of the modern atomic theory is that the mole ratios of elements in a compound will be small whole numbers (the Law of Definite Proportions). The whole-number mole ratio is commonly referred to as the *empirical formula* of a compound.

One of the challenges in finding the proper chemical formula for a compound is the possibility of more than one plausible mole ratio for the elements in that compound. Dalton called this the Law of Multiple Proportions. For example, when testing a compound that contained iron and sulfur, the plausible chemical formula could be FeS or Fe_2S_3. However, once the mass of iron and the mass of sulfur present in a given mass of the compound are determined, the true chemical formula of the compound can be established.

Applying Your Knowledge

1. The student has a combination of iron and oxygen.

   a) What are the possible formulas for the compound?

   FeO and Fe_2O_3

   b) The student obtained the following information regarding the compound. Based on this information, which compound is it?

   Item

Total mass of sample	1.50 g
Grams of iron	1.05 g
Grams of oxygen	0.45 g

   To determine which compound the information applies to, determine the number of moles of each element and then determine the ratio of the number of moles of oxygen to the number of moles of iron:

   $$\frac{1.05 \text{ g Fe}}{1} \times \frac{1 \text{ mol Fe}}{55.845 \text{ g Fe}} = 0.018802 \text{ mol Fe}$$

   $$\frac{0.45 \text{ g O}}{1} \times \frac{1 \text{ mol O}}{15.9994 \text{ g O}} = 0.028126 \text{ mol O}$$

   $$\frac{0.028126 \text{ mol O}}{0.018802 \text{ mol Fe}} = \frac{1.4959 \text{ mol O}}{\text{mol Fe}} \approx \frac{1.5 \text{ mol O}}{\text{mol Fe}} \text{, so the formula is } FeO_{1.5}$$

   Converting the ratio to whole numbers: $2 \times (FeO_{1.5}) = Fe_2O_3$

Teacher Tips

Tip 1 – Heating the hydrate

Do not heat the copper(II) chloride dihydrate with a burner. The compound will decompose at temperatures above 300 °C and form poisonous chlorine gas. If any student's sample begins to emit a yellow gas, immediately remove the sample from the heat. If fume hoods are available, heat the samples under the hood for maximum safety.

As an alternative, an oven can be used and set to a temperature between 150 °C and 200 °C. However, this is a much slower process, taking 15 to 30 minutes to completely dry a sample.

8. MEASURING VITAMIN C—A REDOX TITRATION

Initial Question

Vitamin C, also called *L-ascorbic acid*, is found in many foods. Most people expect orange juice to be the best source of vitamin C but other berries have a higher vitamin C content and juice drinks like Hi-C® have a great deal of added vitamin C. In these cases, it is difficult to perform a traditional acid–base titration because there may be more than one acid present. How can we accurately measure the vitamin C content present in foods?

What foods have the highest levels of vitamin C?

Learning Objectives*

Students expand their understanding of titrations, carry out a redox titration, and then use the redox titration method to answer a question of their own design.

LO 1.20 / The student can design, and/or interpret data from, an experiment that uses titration to determine the concentration of an analyte in a solution.

LO 3.9 / The student is able to design and/or interpret the results of an experiment involving a redox titration.

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

SP 4.3 / The student can *collect data* to answer a particular scientific question

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

Time Requirement

Preparation time: 45 minutes / Lab activity: 90 minutes

Materials and Equipment

Model 1

- Data collection system
- Oxidation reduction potential (ORP) probe[1]
- Beaker (5 for the entire class), 250-mL
- Beaker, 150-mL
- 0.25 % Iodine (I_2) solution, 50 mL for entire class[2]
- 0.01 M L-Ascorbic acid ($C_6H_8O_6$), 50 mL for the entire class[2]

- 3% Hydrogen peroxide (H_2O_2), 50 mL for entire Class[4]
- 0.01 M Potassium permanganate ($KMnO_4$), 50 mL for the entire class[4]
- 1.0 M Sodium chloride (NaCl), 50 mL for the entire class[4]
- Distilled water, 50 mL

[1]Use with PASCO Advanced Chemistry Sensor.

[2]To prepare the iodine solution from povidone iodine or from solid I_2 and KI, refer to the Lab Preparation section.

[3]To prepare the vitamin C standard using L-ascorbic acid or vitamin C tablets; refer to the Lab Preparation section.

[4]To prepare the H_2O_2, $KMnO_4$, and NaCl solutions, refer to the Lab Preparation section.

Model 2 and Applying Your Knowledge

- Data collection system
- Oxidation reduction potential (ORP) probe[1]
- Drop counter
- Drop dispenser:
  Syringe, 60-mL
  Stopcock (2)
  Drop tip

- Multiclamp
- Three-finger clamp
- Ring stand
- Beaker, 150-mL
- Magnetic stir plate and micro stir bar
- Analytical balance
- Materials for drop counter and pH sensor calibration (refer to Appendix A)

[1]Use with PASCO Advanced Chemistry Sensor.

Model 2

0.25 % Iodine (I_2) solution, 70 mL[1]

L-Ascorbic acid ($C_6H_8O_6$), 0.040–0.060 g[2]

- Distilled water, 75 mL

[1]To prepare the iodine solution from povidone iodine or from solid I_2 and KI, refer to the Lab Preparation section.
[2]To prepare the vitamin C standard using L-ascorbic acid or vitamin C tablets; refer to the Lab Preparation section.

Applying Your Knowledge

- 0.25 % Iodine (I_2) solution, as needed[1]
- Foods or juices for vitamin C analysis[2]

- Juicer
- Knife (for slicing fruit)

[1]To prepare the iodine solution from povidone iodine or from solid I_2 and KI, refer to the Lab Preparation section.
[2]Refer to the Lab Preparation section for suggested foods and juices.

Prerequisites

Students should be familiar with the following concepts:

- Acid–base titrations conducted with a pH probe
- Oxidation–reduction (redox) reactions
- Reaction stoichiometry
- Molarity

Lab Preparation

These are the materials and equipment to set up prior to the lab:

All Models and Applying Your Knowledge

1. **0.25% Iodine solution**: Make the 0.25% iodine solution from either povidone iodine from a drug store or from solid I_2 and KI. Both methods are listed below.

   a. **0.25% Iodine solution from I_2 and KI**: Prepare 1000 mL of 0.25% I_2 by placing 2.5 g of I_2(s) and 5 g of KI(s) in about 100 mL of distilled water in a 1000-mL volumetric flask. Stir it well and let it sit. When the solid has completely dissolved, fill the flask to the line with distilled water.

   b. **0.25% Iodine solution from povidone iodine**: Povidone iodine is a mixture of elemental iodine and a polymer that makes it soluble in water and the actual concentration of I_2 may vary.

   Prepare 1000 mL of 0.25% I_2 by placing 25.0 mL of approximately 10% povidone iodine in a 1000-mL volumetric flask. Stir it well and fill the flask to the line with distilled water.

Model 1

Create stations by placing about 50 mL of each of the suggested solutions (iodine, vitamin C, hydrogen peroxide, potassium permanganate, sodium chloride, and distilled water) in a 250-mL beaker. The concentration of these solutions is not of great importance, so you can use 3% H_2O_2 from the drug store and any concentration of $KMnO_4$ that may be available from previous experiments.

NOTE: If you place the solutions in a smaller beaker, you increase the risk that a student will knock over the beaker while trying to perform the measurement.

2. **0.01 M Vitamin C**: Prepare 100 mL of 0.01 M L-Ascorbic acid by placing 0.1761 g of solid L-ascorbic acid in about 25 mL of distilled water in a 100-mL volumetric flask. Stir it well and let it sit. When the solid has completely dissolved, fill the flask to the line with distilled water.

3. **0.01 M KMnO4**: Prepare 100 mL of 0.01 M $KMnO_4$ by placing 0.1580 g of solid $KMnO_4$ in about 25 mL of distilled water in a 100-mL volumetric flask. When the solid has completely dissolved, fill the flask to the line with distilled water.

4. **1.0 M NaCl**: Prepare 100 mL of 1.0 M NaCl by placing 5.8448 g of NaCl in about 25 mL of distilled water in a 100-mL volumetric flask. Stir it well and when the solid has completely dissolved, fill the flask to the line with distilled water.

Model 2

5. **0.040 – 0.060 g Vitamin C**: Provide students with either L-ascorbic acid or vitamin C supplement tablets.

   If you provide the vitamin supplement tablet, be certain to work out beforehand the mass of tablet that must be used to obtain between 0.040 and 0.060 g of vitamin C. A 500 mg Vitamin C tablet contains 78.18% vitamin C. Vitamin supplement tablets contain binders and other inert ingredients which will not interfere with the titration, but do add mass. Students can multiply 0.7818 times the amount they massed to determine the amount of vitamin C in their sample.

   The above step is not necessary if you provide solid L-ascorbic acid for students to use.

Applying Your Knowledge

6. **Vegetable and fruit preparation**: Your students will need a variety of fruits, vegetables, and juices to conduct the experiment in Model 3. Suggestions are:

   - Fresh oranges and lemons

   - Orange juice, fresh and frozen

   - Lemon juice

   - Green peppers

   - Red peppers

   - Broccoli

   - Knife for slicing citrus fruit

Safety

Add these important safety precautions to your normal laboratory procedures:

- $KMnO_4$ is a strong oxidizer and should be treated as particularly hazardous. If the solution comes in contact with your skin, rinse immediately with a large amount of running water.

Getting Your Brain in Gear

1. Without consulting your textbook or the Internet, give your best definition of the word "titration."

   A titration is a procedure used to determine the number of grams or moles of a compound (the "analyte") by reacting it with another compound (the "titrant") of known concentration and a known stoichiometric relationship to the analyte.

   Students are not expected to come up with this answer. Students generally identify a titration by the equipment (buret) or compounds (acids, bases, and indicators) that are generally associated with titrations.

2. The equation for the reaction between elemental iodine and vitamin C, $C_6H_8O_6$, is

$$I_2(aq) + C_6H_8O_6 \rightarrow 2HI + C_6H_6O_6$$
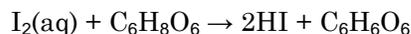
   a. What are the oxidation states of iodine on both sides of the equation?

      In I_2, the oxidation state is 0, in HI the oxidation state is −1.

   b. Is I_2 oxidized or reduced in this reaction?

      The oxidation state is decreased, therefore it is reduced.

   c. Write the half-reaction for I_2 in this oxidation–reduction (or redox) reaction.

      $2e^- + I_2 \rightarrow 2I^-$
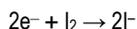
   d. Given your answer to part b, is vitamin C oxidized or reduced during this reaction? Briefly explain your answer.

      Vitamin C is oxidized because redox reactions have one species that is reduced and another that is oxidized.

MODEL 1

Building Model 1 – Measuring the Oxidation Reduction Potential of a Solution

1. Connect the oxidation reduction potential probe (ORP) to your data collection system.

2. The ORP probe measures ISE voltage. Monitor live ISE voltage data without recording.

3. Use the ORP probe to measure the oxidation reduction potential following solutions: $KMnO_4$, H_2O_2, vitamin C, NaCl and distilled H_2O. Rinse the probe with distilled water between each measurement. Record the potential in the Model 1 Data Table.

Model 1 – Measuring the Oxidation Reduction Potential of a Solution

Table 1: Model 1 Data Table—Oxidation reduction potential of various solutions

Solution	Oxidation–Reduction Potential (ISE, mV)	Oxidizer (Strong/Not Strong)
I_2 (aq)	382	s
Vitamin C(aq)	152	ns
H_2O_2 (aq)	345	s
$KMnO_4$	500	s
NaCl(aq)	170	ns
Distilled H_2O	172	ns

Analyzing Model 1 – Measuring the Oxidation Reduction Potential of a Solution

4. What solutions in the Model 1 Data Table would you group together as having high oxidation reduction potentials and which would you group together as having low potentials?

   $KMnO_4$, H_2O_2, and I_2 solutions have high oxidation reduction potentials; vitamin C, NaCl, and H_2O have low potentials.

5. Potassium permanganate, $KMnO_4$, and hydrogen peroxide, H_2O_2, are both strong oxidizers. This means that they often cause other compounds to be oxidized while they are reduced. Strong oxidizers are highly reactive with other compounds, must not be ingested, and must be stored carefully. Vitamin C and water are not strong oxidizers.

   a. You should see a pattern between the oxidation reduction potential and oxidation strength of the solutions mentioned. Using this pattern, indicate in the Model 1 Data Table whether each solution is a strong oxidizer "s" or not a strong oxidizer "ns".

      NOTE: Strong oxidizers are greater than 250 mV.

   b. Based on this information, what is the ORP probe actually measuring?

      The ORP probe is measuring the oxidizing ability of the solution.

6. Is aqueous sodium chloride a strong oxidizer? Does this make sense with what you know about NaCl?

   No, it is not a strong oxidizer; neither the sodium nor the chloride has changed oxidation number. Also, we put it on food and ingest it.

7. Model 2 involves adding iodine, I_2, solution to the vitamin C solution until all of the vitamin C is consumed. On the blank graph below, sketch your prediction for the shape of the graph of ISE voltage versus the volume of iodine added to the vitamin C solution.
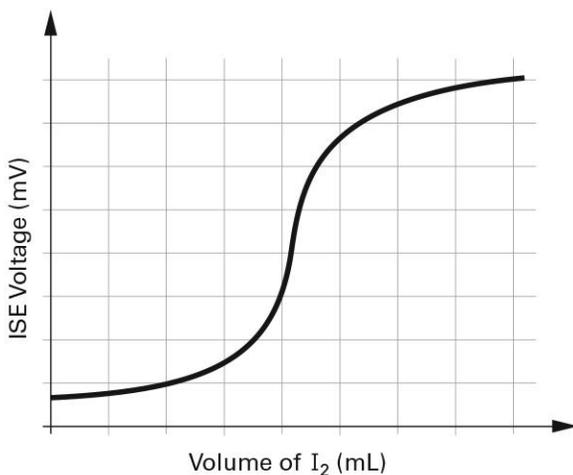
The correct shape is a titration curve. The expected answer, however, is a straight line between the vitamin C reading and the I_2 reading.

MODEL 2

Building Model 2 – Reacting Vitamin C with Iodine

1. Obtain about 60 mL of iodine solution in a beaker.

2. Obtain a drop dispenser and a drop counter. Set up the drop counter as shown in the diagram.

3. Connect the drop counter to the data collection system.

4. Display ISE voltage on the *y*-axis of a graph and fluid volume on the *x*-axis.

5. Rinse the drop dispenser three times with 2 to 3 mL of distilled water and then rinse it three times with 2 to 3 mL of I_2 solution.

6. Fill the drop dispenser with the I_2 solution.

7. Set the flow rate of the drop dispenser and calibrate the drop counter as described in Appendix A.

    NOTE: Do not disconnect the drop counter from the data collection system or it will need to be calibrated again.
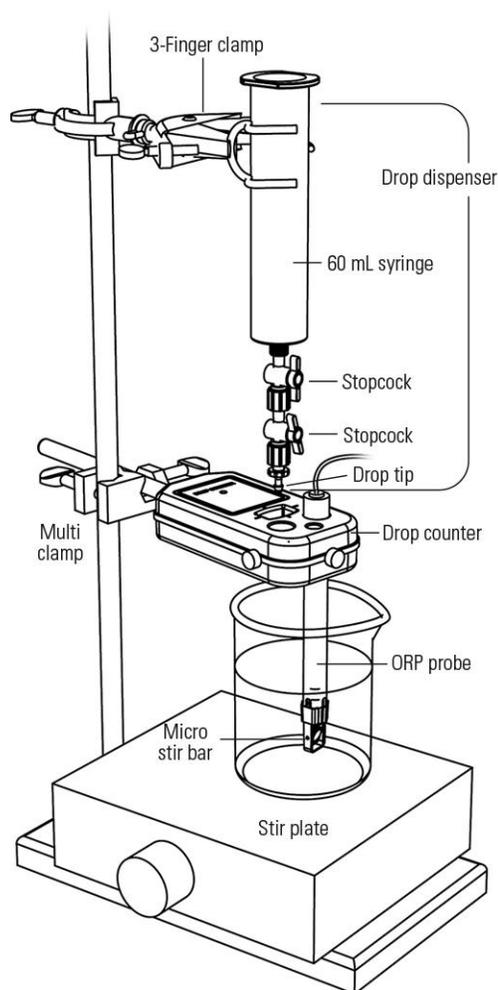
8. Obtain between 0.040 and 0.060 g of L-ascorbic acid, vitamin C, and dissolve it in about 75 mL of distilled water in a 150-mL beaker. Record the exact mass of L-ascorbic acid in the Model 2 Data Table below.

   NOTE: If you are using vitamin C tablets rather than L-ascorbic acid, make sure to convert the mass of the tablet measured to the mass of vitamin C, as vitamin C tablets contain binders and other inert ingredients which will not interfere with the titration but do add mass.

9. Obtain a stir plate and stir bar. Add the stir bar to the beaker containing the vitamin C solution. Turn on the magnetic stirrer at a slow and steady rate.

10. Start recording data. Turn the drop dispenser stopcock carefully, allowing the I_2 solution to drip slowly at a rate of 1 to 2 drops per second into the vitamin C solution.

    NOTE: The top valve controls the flow rate and the bottom valve turns the flow on and off.

11. Sketch or attach a copy of the graph of ISE voltage versus volume of $KMnO_4$ in the Model 2 data section.

Model 2 – Reacting Vitamin C with Iodine

Mass of vitamin C: _____0.052 g_____

Determining the concentration of vitamin C
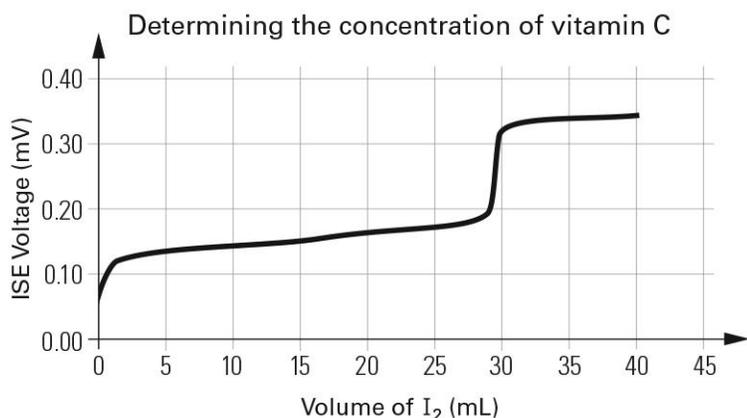
Analyzing Model 2 – Reacting Vitamin C with Iodine

12. a. Does your observed graph match your predicted graph? Explain any differences.

    This depends on students' predictions, but it is not expected that their prediction will match the observed graph.

    b. What type of graph does your data resemble?

    The graph resembles an acid–base titration curve.

13. As you have probably guessed by now, the experiment you just conducted was a titration.

    a. Does this experiment fall under the definition of "titration" you gave in the "Getting Your Brain in Gear" question?

    Expected answer: No.

b. Revise your definition of titration based on your experience in lab. Avoid using any reference to color changes or the equipment you use.

A titration is a procedure used to determine the number of grams (or moles) of a compound (the "analyte") by reacting it with another compound (the "titrant") of known concentration and a known stoichiometric relationship to the analyte.

14. At what volume of I_2 is all of the vitamin C consumed? How does the graph indicate this?

Volumes will vary. All of the vitamin C is consumed at the point when the graph suddenly jumps. For the sample data shown above, that volume is 29.3 mL.

15. Using the measured mass of vitamin C, calculate the following:

a. The number of moles of iodine necessary to react completely with the vitamin C.

Since one mole of iodine reacts with one mole of vitamin C, for the sample data:

$$0.052 \text{ g vitamin C} \times \frac{1 \text{ mol vitamin C}}{176.12 \text{ g vitamin C}} \times \frac{1 \text{ mol } I_2}{1 \text{ mol vitamin C}} = 2.9 \times 10^{-4} \text{ mol } I_2$$

b. The molarity of the iodine solution.

$$\frac{2.9 \times 10^{-4} \text{ mol } I_2}{0.0293 \text{ L}} = 0.0101 \text{ M } I_2$$

16. Collect the molarity of I_2 from other groups.

Table 2: Compare class results of the molarity of the iodine solution

Group	I_2 Concentration (M)
1	0.0101
2	0.0116
3	0.0130
4	0.0120
5	0.0120
6	
7	
8	
9	
10	
11	

a. Calculate the standard deviation.

For the sample data:

$$\text{Standard deviation} = \sqrt{\frac{\sum (x - \bar{x})^2}{n}}$$

$\bar{x}$ = Mean = 0.0117 M

n = the number of values = 5

Standard deviation = 0.0009

b. Remove molarities that are outside of the standard deviation and then calculate the average concentration. You will use this value for the calculations for the Applying Your Knowledge experiment. This process of determining the concentration of a solution to be used in a later experiment is called *standardization*.

Average molarity of the I_2 standard solution :   0.0119 M

Calculation of the data range within the standard deviation:

0.0117 M + 0.0009 M = 0.0126 M

0.0117 M – 0.0009 M = 0.0108 M

For the sample data, the valid molarities are between 0.0108 M and 0.0126 M inclusive.

Calculation for the average concentration:

(0.0116 M + 0.0120 M + 0.0120 M)/3 = 0.0356/3 = 0.0119 M

Connecting to Theory

Vitamin C functions as an anti-oxidant in humans. This means that it causes reduction to occur in other substances. However it only displays weak anti-oxidant abilities, and like weak acids and bases, the oxidation reduction potential of vitamin C is reversible. The anti-oxidant reversibility is a function of pH.
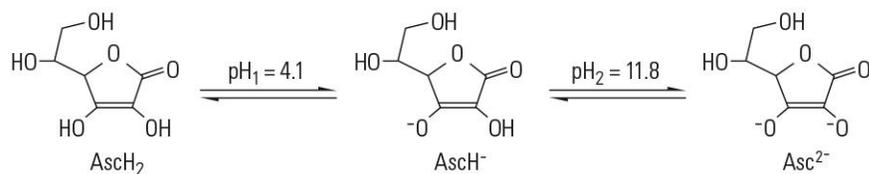
The illustration is a simplified version of the pathway the ascorbate ion undergoes. Eight forms of the ion have been categorized. But as you can see, there are two major changes, one at pH of 4.1 and one at pH 11.8. The middle figure is dominant at pH 7.4. The ability of vitamin C to cause reduction makes it an ideal candidate for ORP titration.

Applying Your Knowledge – Determining the Concentration of Vitamin C in Juice

1. Design an experiment that uses the standardized iodine solution from Model 2. Create a hypothesis you will test related to the vitamin C content of available materials.

   Example hypotheses:

   Boiling orange juice changes its vitamin C content.

   Fresh orange juice has higher vitamin C content than frozen orange juice.

2. Once you know what materials are available, answer the following questions *before* beginning the experiment.

   a. What hypothesis would you like to test?

   Most hypotheses will fall into one of the following categories:

   - Fresh juice has a higher vitamin C concentration than canned, frozen, or juice from concentrate.
   - Juice of one type of fruit has a higher vitamin C concentration than another.
   - Freezing, heating, or boiling a fruit will change its vitamin C concentration.
   - Citrus fruits have a higher vitamin C concentration than vegetables.

   The hypothesis for the sample data is, "Orange juice drink has more vitamin C than all other juice drinks."

    b. What data will you need to collect?

The data to collect includes the mass or volume of the vitamin C source and the volume of I_2 necessary to consume the vitamin C. (Students will often forget the first of these!)

    c. What conditions will need to be held constant between your two titrations?

For the sample data, the volume of juice used and the concentration of I_2 were held constant. Answers will vary based on the chosen hypothesis.

3. Outline the procedure of your experiment.

Answers will vary, but all should include titrating solutions with the standardized I_2 solution.

4. Carry out the experiment to test your hypothesis. Record your data. Modify the data table as needed.

Molarity of I_2:   0.0119 M

Table 3: Data Table

Vitamin C Source		Volume of Juice (mL)	Volume of I_2 (mL)	Concentration of Vitamin C (M)	Average Concentration (M)
SunnyD Orange Juice	Run 1	10.10	2.76	3.25×10^{-3}	3.22×10^{-3}
	Run 2	10.01	2.70	3.20×10^{-3}	
Ocean Spray Cranberry Pomegranate Juice	Run 1	10.09	1.19	1.40×10^{-3}	1.44×10^{-3}
	Run 2	10.20	1.27	1.48×10^{-3}	
Crystal Geyser Juice Squeeze Wild Berry	Run 1	10.20	0.10	1.2×10^{-4}	1.38×10^{-4}
	Run 2	12.40	0.17	1.6×10^{-4}	

5. Provide calculations for your experiment that either prove or disprove your hypothesis.

Example calculation for determining the vitamin C content of Sunny D Orange Juice, Run 1:

$V_1M_1 = V_2M_2$

10.10 mL $\times$ x mol/L = 2.76 mL $\times$ 0.0119 mol/L

$x = 3.25 \times 10^{-3}$ M

My hypothesis was proved correct. SunnyD orange juice had the highest concentration of vitamin C at 3.22×10^{-3} M. Ocean Spray Cranberry Pomegranate juice has the second highest at 1.44×10^{-3} M and Crystal Geyser Juice Squeeze Wild Berry has the least amount of vitamin C at 1.38×10^{-4} M.

6.   Compare your experiment to others in class. How could your experiment have been improved?

The extraction of fruit juices could be more thorough.

More trials of juice.

7. Vitamin C is an acid. Why was it necessary in this lab to use the ORP probe rather than the pH sensor?

In Model 3 we analyzed orange juice, which contains a mixture of acids, including vitamin C. In order to determine the concentration of the vitamin C in the juice, it was necessary to use the compound I_2, which reacts only with the vitamin C. Since this is a redox reaction, the ORP probe was used.

Teacher Tips

Tip 1 − Iodine considerations

The price of povidone iodine can vary significantly from one store to another, so you may want to research different sources prior to purchasing it.

If purchasing solid I_2, realize that it can be used as an illicit drug precursor, so may take a little longer than expected to obtain. Take extra care to keep it locked in your storeroom.

Tip 2 – Calibrating the drop counter

Students need to calibrate the drop counter before carrying out the titration If the drop counter has been disconnected from the data collection system between titrations, students will need to calibrate it again before carrying out the titration. The calibration procedure is in Appendix A.

Tip 3 – Purchasing fruits and vegetables

Be sure to provide red and green peppers and encourage some students to use them. No food has a higher concentration of vitamin C than red peppers.

Bottled juices are often a blend of more than one juice and may contain added vitamin C. Students should be aware of all ingredients when incorporating such juices into their experiment.

Tip 4 – Model 3 experiment design

To maximize class time in lab, you may wish to have students complete the design questions as homework the night before this portion of the lab.

Students will run into the problem of how much juice or fruit to use. In order to get detectable amounts and quality data, students need to choose amounts that will have at least 25 mg of vitamin C. You can direct them to do an Internet search to find the expected quantity for the food, but 20 mL of juice, half an orange, or 1 lemon in a 50 mL beaker is a good starting point.

Make sure students have included the mass of their food as one of the data they must collect. Students will often begin an experiment to determine the "amount of vitamin C," not realizing that in order to make a good comparison, they really want the vitamin C concentration. They cannot calculate this if they do not know the original mass of the fruit or vegetable. Alternatively, students can eliminate this problem if they use equal amounts (mass or volume) of the foods they are comparing.

Tip 5 − Iodine in aqueous solutions

The iodine solution prepared in this lab, using either $I_2(s)$ and KI or povidone iodine, does not actually contain $I_2(aq)$. Both solutions actually contain $I_3^-(aq)$. This is why KI is necessary for the solution made from solid iodine. The I^- ion will convert I_2 to I_3^-. However, as is generally done, the species is written as "$I_2(aq)$" to minimize confusion for the students.

Tip 6 − The historical discovery of Vitamin C

Vitamin C was first isolated from red peppers (of the sort used to make paprika powder) by a Hungarian chemist, Albert Szent-Gyorgyi, who received the 1937 Nobel Prize in Medicine and Physiology for his work. For a more extensive discussion, you can see the Nobel Prize website or read Chapter 2 in *Napoleon's Buttons: How 17 Molecules Changed History* by Penny LeCouteur and Jay Burreson.

9. FACTORS THAT AFFECT REACTION RATE

Initial Question

In some cases we want reactions to proceed quickly, for example, for air bag deployment or certain processes used in manufacturing. In other cases, we want reactions to proceed slowly, such as the corrosion of car parts or aging. Scientists have discovered many factors, or variables, that can be manipulated to change the rate of a reaction. In this investigation, you explore one factor that may alter the rate of a reaction and share what you've found with your classmates.

How can we speed up or slow down a chemical reaction?

Learning Objectives[*]

In this lab, students explore, through student-designed procedures, several variables that could affect the rate of a chemical reaction. The system of study is calcium carbonate and hydrochloric acid. The production of carbon dioxide will be monitored using a pressure sensor.

LO 4.1 / The student is able to design and/or interpret the results of an experiment regarding the factors (i.e. temperature, concentration, surface area) that may influence the rate of a reaction.

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

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

Time Requirement

Preparation time: 20 minutes / Lab activity: 90 minutes

Materials and Equipment

Model 1 and Model 2

- Data collection system
- Temperature sensor
- Pressure sensor
- Quick-release connector[1]
- Tubing, 1- to 2-cm[1]
- Tubing connectors[1]

- Two-hole stopper to fit flask
- Erlenmeyer flask, 125-mL
- Graduated cylinder, 50-mL
- Syringe, 60-mL
- Mortar and pestle

[1]Included with PASCO Advanced Chemistry Sensor

Model 1

- Calcium carbonate ($CaCO_3$), solid, 0.2 g
- 3.0 M Hydrochloric acid (HCl), 1 mL

- Distilled water, 50 mL

---

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Model 2

- Equipment and amounts depend on the variable:

Beaker for ice bath	Hot plate
Beaker (4), 50-mL	Calcium carbonate ($CaCO_3$)
Graduated cylinder, 10-mL	3.0 M Hydrochloric acid (HCl)
Magnetic stir bar	Ice
Stir plate	Distilled water

Prerequisites

Students should be familiar with the following concepts:

- Ideal Gas Law equations

- Kinetic Molecular Theory

- Collision Theory

- Independent, dependent, and controlled variables

Lab Preparation

These are the materials and equipment to set up prior to the lab:

Model 1 and Model 2

3.0 M Hydrochloric acid: To prepare 500 mL of 3.0 M hydrochloric acid (HCl), fill a 500-mL volumetric flask 1/3 full of distilled water. Add 125.0 mL of concentrated hydrochloric acid (12 M) to the flask and swirl. Fill the flask to the line with distilled water.

Model 2

In this model, the following variables should be assigned. If the list students brainstorm doesn't include all of them, guide them so they are all present. If students come up with additional variables, add them to this list, as appropriate. Then assign one variable to each student group so all variables are covered. Students share the data for the reactions they haven't done.

- Mass of calcium carbonate

- Surface area of calcium carbonate (extent to which it is crushed)

- Volume of hydrochloric acid added

- Speed/amount of stirring

- Temperature of the calcium carbonate solution

- Volume of water added to the flask

- Concentration of HCl

NOTE: Successful trials seem to be in the range of 0.10–0.60 g of calcium carbonate and 0.5–2.0 mL of 3.0 M hydrochloric acid.

Safety

Add these important safety precautions to your normal laboratory procedures:

- Treat all unknowns as a hazardous, toxic, and harmful material.

- All unknowns will need to be disposed of in the proper waste container.

- Hydrochloric acid is highly corrosive; it will damage human tissue and clothing. If you get hydrochloric acid on your skin, flush the area with large amounts of water.

Getting Your Brain in Gear

1. In this lab, you will be mixing calcium carbonate solid with a solution of hydrochloric acid. Write a balanced equation for the reaction that will occur. Include phase notation.

   $CaCO_3(s) + 2HCl(aq) \rightarrow H_2O(l) + CO_2(g) + CaCl_2(aq)$
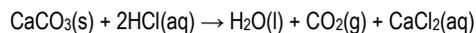
2. Draw a particle-level representation diagram of the balanced equation.
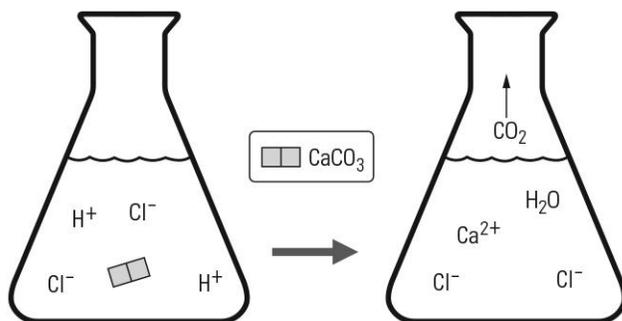
3. Gas pressure is defined as a collision of gas particles. Do the reactants or the products have more gas pressure?

   The products have greater gas pressure.

4. What particles are colliding to make the reaction progress?

   $CaCO_3(s) + 2HCl(aq)$
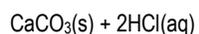
5. Which of the following would have more collisions? Justify your answer.
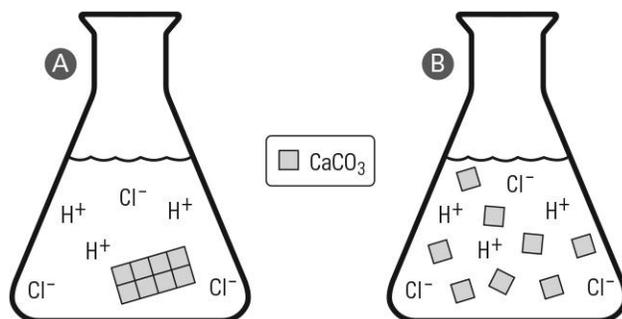
   The solution in flask B will have more collisions. When the number of particles increases, so does the surface area, so flask B will have more collisions.

MODEL 1

Building Model 1 – The Change in Pressure during a Reaction

1. Prepare the reaction apparatus by completing the following steps.

   a. Connect the pressure sensor to the two-hole stopper: place the barbed connector of the pressure sensor tightly into the rubber stopper and connect it to the pressure port of the sensor with a piece of tubing.

   b. Connect the syringe to the stopcock connected to the other hole of the two-hole stopper. Close the stopcock.

   c. Place the two-hole stopper tightly into the 125-mL Erlenmeyer flask.

   d. Check for leaks in the system by opening the stopcock, pulling up on the syringe, and holding for 10 seconds. Then release the plunger of the syringe. It should return to its original position if there are no leaks.
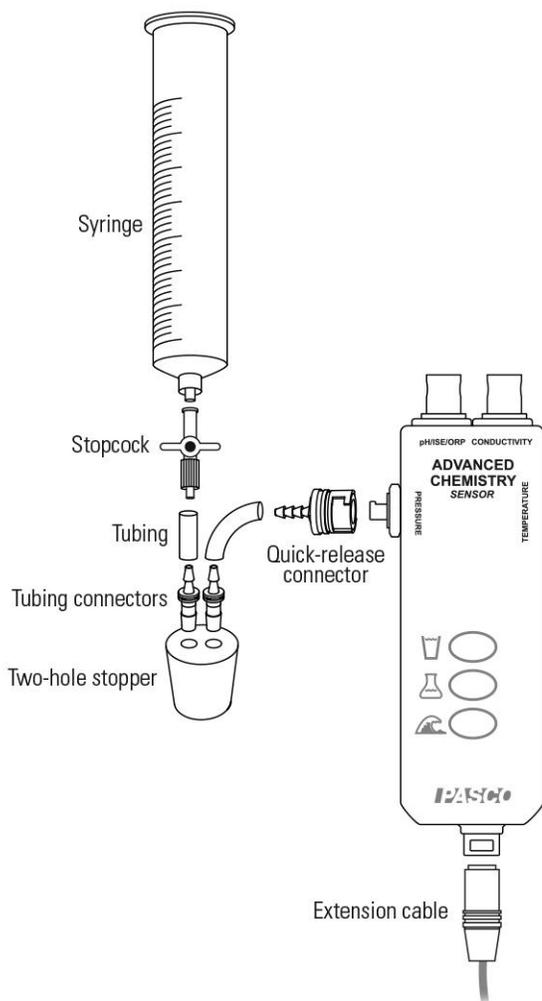
2. Connect the pressure sensor and temperature sensor to the data collection system and start a new experiment. Display the pressure on the *y*-axis of a graph and time on the *x*-axis

3. Break off a small piece of white chalk (which is primarily calcium carbonate) and use the mortar and pestle to crush it into a fine powder. Measure approximately 0.2 g of the chalk powder. Record the mass in the Model 1 Data Table. Transfer the calcium carbonate sample to the 125-mL Erlenmeyer flask quantitatively.

4. Add 50 mL of distilled water to the Erlenmeyer flask, reinsert the stopper into the flask, and check again for leaks.

5. Close the stopcock and remove the syringe. Remove the plunger and place 1.0 mL of 3.0 M hydrochloric acid (HCl) into the syringe, keeping the syringe horizontal so the solution doesn't spill out. Replace the plunger and return the syringe to the reaction apparatus by twisting it gently back onto the stopcock.

   NOTE: Because of the short tubing, the syringe sits vertically above the flask.

6. Begin data collection. Record the pressure in the Erlenmeyer flask for 10 seconds.

7. At the ten second mark open the stopcock. If the contents of the syringe do not completely empty into the reaction flask, apply gentle pressure to the plunger. Once this transfer has occurred, quickly close the stopcock once again.

8. Gently swirl the flask while collecting data for at least 5 minutes.

9. Record the room temperature in the Model 1 Data Table after converting it to Kelvin.

❷ 10. Which of the following gases are in the flask in quantities greater than or equal to at least ~1% before the HCl is introduced?

| Nitrogen | Oxygen | Argon | Chlorine |
| Carbon dioxide | Water vapor | Hydrogen | Carbon monoxide |

Air (nitrogen, oxygen, argon) and water vapor.

❷ 11. Which of the gases are in the flask after the reaction has occurred?

Air (nitrogen, oxygen, argon), water vapor, and carbon dioxide.

❷ 12. Explain why the pressure is increasing in the flask during the reaction. Support your answer with concepts from the kinetic molecular theory.

Carbon dioxide gas is being produced in the reaction. Since there are more molecules of gas in the same volume, there will be more collisions with the sides of the container and the pressure probe, so the pressure increases.

13. Use the time versus pressure graph to determine the pressure in the flask at 10 seconds and at 3 minutes. Record these values in the Model 1 Data Table.

Model 1 – The Change in Pressure during a Reaction

Table 1: Model 1 Data Table—Reaction measurements and results

Parameter	Value
Volume of reaction vessel (mL)	125 mL
Mass of chalk ($CaCO_3$) (g)	0.2178 g
Volume of 3.0 M HCl (mL)	1.0 mL
Pressure of gas at 10 sec (kPa)	103 kPa
Pressure of gas at 3 minutes (kPa)	125 kPa
Room temperature	298.5 K

Analyzing Model 1 – The Change in Pressure during a Reaction

14. Calculate the partial pressure of carbon dioxide in the flask at 3 minutes. Assume there was no carbon dioxide in the flask before the reaction.

Subtracting the initial pressure from the final pressure: 125 kPa – 103 kPa = 22 kPa

15. Calculate the number of moles of carbon dioxide in the flask at 3 minutes using the Ideal Gas Law.

NOTE: Some of the flask volume was occupied by liquid and solid. Assume the volume of the gas is the same as the Erlenmeyer flask 125 mL, or 0.125 L.

$PV = nRT$

$22 \text{ kPa} \times 0.125 \text{ L} = n \times 8.31 \dfrac{\text{kPa L}}{\text{mol K}} \times 298.5 \text{ K}$

$n = 1.1 \times 10^{-3} \text{ mol } CO_2$

16. Calculate the rate of reaction with respect to the production of carbon dioxide for the trial in Model 1.

$\dfrac{1.1 \times 10^{-3} \text{ mol}}{170 \text{ s}} = 6.5 \times 10^{-6} \dfrac{\text{mol}}{\text{s}}$

17. Compare your rate to that of other groups. Is there appreciable difference in the rates? What should be done if a lab group has data that is very different from the rest of the class?

Answers will vary. If the data of one group is significantly different from the rest of the class, that group should run the experiment again.

MODEL 2

Building Model 2 – Factors That Affect Rate

1. List at least five variables that could be tested with the same reaction system as Model 1 to determine if they affect the rate of the reaction. Be prepared to share your list with the class.

Mass of calcium carbonate

Surface area of calcium carbonate (extent to which it is crushed)

Volume of hydrochloric acid added

Speed and amount of stirring

Temperature of the calcium carbonate solution

Volume of water added to the flask

Concentration of HCl

2. Your instructor will assign a variable for you to test using the reaction system in Model 1. Develop a procedure for a controlled experiment to test that variable. You will need at least four trials. Record your procedure below and design the Model 2 Data Table.

List the variable(s) in each category for the lab procedure you develop:

Independent:	Mass of $CaCO_3$
Dependent:	Pressure
Controlled:	Volume of 3.0 M HCl

Procedure:

1. Use the same setup and procedure as in Model 1.

2. Keep the volume of the 3.0 M HCl added constant at 1.0 mL.

3. Vary the mass of $CaCO_3$ by approximately 0.2 g starting with 0.2 g and ending with 0.6 g.

3. Calculate the rate of reaction for each trial. Use the calculations you performed in Model 1 as an example.

Using the sample data:

Partial pressure = $P_{3min} - P_{10s}$ = 107.9 kPa – 101.2 kPa = 6.7 kPa

Determine the number of moles of CO_2 generated per second:

$$n = \frac{PV}{RT} = \frac{6.7 \text{ kPa} \times 0.125 \text{ L}}{8.31 \frac{\text{mol K}}{\text{L kPa}} \times 298.5\text{K}} = 3.4 \times 10^{-4} \text{mol}$$

$$\frac{3.4 \times 10^{-4} \text{ mol}}{170 \text{ s}} = 2.0 \times 10^{-6} \text{ mol/s}$$

4. In the Model 2 data section, sketch or attach a copy of your graph that shows the relationship between the rate of reaction and your independent variable. Be prepared to share your findings with the class.

Model 2 – Factors That Affect Rate

Sample data for an increasing mass of $CaCO_3$

Mass of $CaCO_3$ (g)	Volume of 3.0 M HCl (mL)	Pressure after 10 Seconds (kPa)	Pressure after 3.0 Minutes (kPa)	Partial Pressure (kPa)	Amount of CO_2 (mol)	Rate of CO_2 Production (mol/s)
0.1101	1.0	101.2	107.9	6.7	3.4×10^{-04}	2.0×10^{-06}
0.2063	1.0	101.1	110.1	9.0	4.5×10^{-04}	2.6×10^{-06}
0.4282	1.0	101.2	112.7	11.5	5.8×10^{-04}	3.4×10^{-06}
0.6260	1.0	101.1	112.8	11.7	5.9×10^{-04}	3.5×10^{-06}

Rate CO_2 produced vs mass of $CaCO_3$
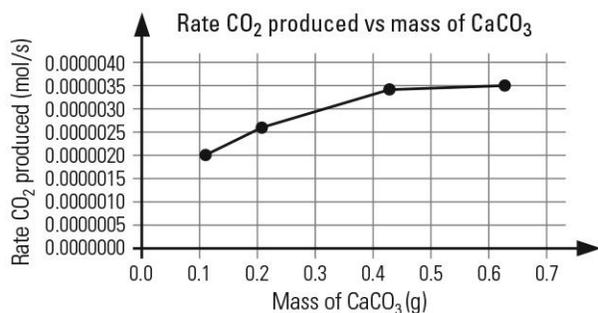
Analyzing Model 2 – Factors That Affect Rate

5. As your classmates summarize their findings, fill in the following relationships. The first blank is for the independent variable. The second blank should be "increased," "decreased," or "stayed the same."

Observations:

A: As   the mass of $CaCO_3$ increased, the rate of reaction   increased

B: As   the surface area of $CaCO_3$ increased, the rate of reaction   increased

C: As   the volume of HCl added   increased, the rate of reaction   increased

D: As   the speed or amount of stirring   increased, the rate of reaction   stayed the same

E: As   increase temperature of the $CaCO_3$ solution   increased, the rate of reaction   increased

F: As   the volume of water added to the flask   increased, the rate of reaction   stayed the same

G: As   diluting the concentration of HCl   increased, the rate of reaction   decreased

Connecting to Theory

A reaction mechanism is a series of chemical reactions that illustrate the actual pathway reactants undergo to become products. This usually involves several steps. When the steps are combined, reactants that appear on opposite sides of the arrows cancel, resulting in the net ionic equation. For example,

$$1. \quad CaCO_3(s) + H^+ + Cl^- \rightleftharpoons Ca^{2+} + HCO_3^- + Cl^-$$

$$2. \quad \underline{ HCO_3^- + H^+ + Cl^- \rightleftharpoons CO_2(g) + H_2O + Cl^- }$$

Net ionic equation: $\quad CaCO_3(s) + 2H^+ \rightleftharpoons CO_2(g) + H_2O + Ca^{2+}$

One of the steps usually takes significantly more time to complete than the others. The slower step is known as the *rate determining* step. It is so slow compared to the others that we consider it to take all of the reaction time and the other steps to take no time at all.

The order of the reaction is determined by the slow step. If step 1 in this example is the rate determining step, then the reaction is first order with respect to both $CaCO_3$ and HCl, represented as $H^+ + Cl^-$, because one $CaCO_3$ molecule is reacting with one HCl molecule. However if step 2 is the rate determining step, the reaction is zero order with respect to $CaCO_3$ because it does not appear in that step and first order with respect to HCl because one HCl molecule is present.

This reaction is convenient for laboratory use but difficult to use when writing a rate law because $CaCO_3$ is a solid. The rate law is in the form: Rate $= k[a]^m[b]^n$, where "k" is the rate constant, "a" and "b" are the reacting species and "m" and "n" are the respective reaction orders. The brackets refer to the concentration of the reactant.

Since $CaCO_3$ is a solid, it cannot have a concentration. The value for $CaCO_3$ does not appear in the rate law. It becomes incorporated into the rate constant.

Applying Your Knowledge – Analyzing Model 2

The reactants in a reaction mechanism must collide before they can become products. Chemists use the Collision Theory to explain observations related to reaction rate and to predict how certain variables might alter the rate of a reaction. The Collision Theory states:

- For a reaction to occur, reactant particles must collide.

- For a reaction to occur, the particles in the collision must have sufficient energy to overcome the activation energy for the reaction.

- For a reaction to occur, the particles in the collision must be oriented correctly.

1. If a collision between reactant particles is required for a reaction, what should happen to the rate of reaction if the number of collisions per second is increased?

   The rate should increase.

2. Which of the variables tested in this lab would affect the number of collisions per second between reactant particles?

   The temperature, concentration of HCl, the mass of $CaCO_3$, the surface area of $CaCO_3$, and the volume of the same concentration of HCl added affect the number of collisions per second between reactant particles.

3. Refer to Model 2. Do the observations made in the lab support or refute your answer to the previous question? List specific examples and discuss any discrepancies.

   Yes, the sample data above shows that as the amount of $CaCO_3$ increased the reaction rate also increased. The class results for the list of variables should also support the answer.

4. If the particles in a reaction have sufficient energy for a collision to be successful, what should happen to the rate of reaction if the average kinetic energy of the system is increased?

    The rate of reaction increases with increased kinetic energy.

5. Which of the variables tested in this lab would affect the average kinetic energy of the system?

    Changes to the temperature would affect the average kinetic energy of the system.

6. Do the observations made in Model 2 support or refute your answer to the previous question? List specific examples and discuss any discrepancies.

    From the class summary, students should find that as the temperature increases, the reaction rate increases.

7. Were there any variables tested in Model 2 that affected the rate and were not discussed in previous questions? If yes, propose how the variable tested relates to the collision theory and therefore affects the rate of reaction.

    This depends on the variables the class chooses. Look for things your class may have forgotten.

Teacher Tips

Tip 1 – Student-designed Procedure

The students should be required to write a logical procedure and get it approved by an instructor before proceeding with the lab. This ensures safety and gives the instructor a chance to guide students if their procedure is not going to control enough variables. All of the variables above, except the one they have been assigned to test, should be controlled in their procedure.

Tip 2 - Time Savers for Model 2

Testing the effect of temperature on the reaction is labor intensive because it requires use of hot plates and ice baths. To make the assignment equitable, assign more than one group to that variable and allow the groups to split up the work so that each group does one or two different temperatures.

You may want to give students some guidelines for the amounts of calcium carbonate and hydrochloric acid to use in the flask. If you have limited time, students will get frustrated when their efforts are wasted if the reaction produced too much gas and popped the stopper off before useful data was collected. On the other hand, that can be a very practical lesson for students if your time is more flexible. Successful trials seem to be in the range of 0.10–0.60 g of calcium carbonate and 0.5–2.0 mL of 3.0 M hydrochloric acid.

10. MEASURING THE SPEED OF A REACTION

Initial Question

You have seen instructions on bottles of medicine instructing you, for example, to take "two capsules every four hours." How do scientists come up with how often to take a medication? The answer is that they have done experiments that quantify how quickly the medicine is metabolized by the body. In other words, they develop equations that predict how long it will be before the concentration drops too low to have an effect on your symptoms. Such problems require scientists to make quantitative predictions, that is, to find an equation for the reaction.

How do you determine the speed of a reaction?

Learning Objectives[*]

Students determine the order of a reaction and the effect of variables on the reaction rate.

LO 4.2 / The student is able to analyze concentration versus time data to determine the rate law for a zeroth-, first-, or second-order reaction.

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

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

SP 5.3 / The student can *evaluate the evidence provided by data sets* in relation to a particular scientific question.

Time Requirement

Preparation time: 20 minutes / Lab activity: 90 minutes

Materials and Equipment

Model 1
- Data collection system
- Colorimeter
- Cuvette[1]
- Test tubes (2), 20- to 25-mL
- Volumetric pipets (2), 10-mL

- Beaker, 50-mL
- 5.0×10^{-3} M Crystal violet ($C_{25}H_{30}N_3Cl$), 10 mL[2]
- 0.2 M Sodium hydroxide (NaOH), 10 mL[2]
- Distilled water for calibration, about 10 mL
- Kimwipes®

Model 2
- Data collection system
- Colorimeter
- Cuvette[1]
- Temperature sensor
- Beakers (2), 50-mL[3]
- Beakers (2), 400-mL[3]
- Volumetric pipets (2), 10-mL[3]

- 0.2 M Sodium hydroxide (NaOH), 40 mL[2,3]
- 5.0×10^{-3} M Crystal violet ($C_{25}H_{30}N_3Cl$), 40 mL[2,3]
- Hot plate
- Ice
- Distilled water for calibration, about 10 mL
- Kimwipes®

[1]Included with PASCO Colorimeter.

[2]To formulate these solutions, refer to the Lab Preparation section.

[3]The quantity or volume needed depends on the experiments students create.

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Prerequisites

Students should be familiar with the following concepts:

- Molarity

- Beer's Law

- Factors that affect the rate of a reaction

- Integrated rate laws

Lab Preparation

These are the materials and equipment to set up prior to the lab:

Model 1 and Model 2

1. **2.5×10^{-3} M Crystal violet stock solution**: Because the students' solution is so dilute, it is necessary to make a stock solution first and then dilute that solution to the final concentration. Wear gloves to avoid staining your hands.

   Dissolve 0.1 g of solid crystal violet in about 200 mL of distilled water in a 1-L volumetric flask and then fill it to the line with distilled water.

   Alternatively, starting from a 1% solution of crystal violet, place 50 mL of 1% solution in a 1-L volumetric flask and fill it to the line with distilled water.

   a. **5.0×10^{-6} M Crystal violet**: Measure 2.0 mL of the 2.5×10^{-3} M stock solution into a 1-L volumetric flask and fill to the line with distilled water.

2. **0.2 M NaOH**: Prepare 500 mL of 0.2 M NaOH by placing 4.0 g of solid NaOH in about 100 mL of distilled water in a 500-mL volumetric flask. Stir it well and let it sit (dissolving NaOH evolves a significant amount of heat). When the solid has completely dissolved, fill it to the line with distilled water.

Model 2

NOTE: You may wish to speed up Model 2 by assigning different temperatures to different groups. This is particularly effective if you wish to then lead a discussion about the Arrhenius relationship as you could collect the results of six or more different temperatures.

Choose temperatures below 55 °C, which is the upper limit of good (or acceptable) data quality (as can be seen in the Model 2 Data). At higher temperatures, the reaction goes so quickly that it is difficult to get the solutions mixed and in the colorimeter fast enough to catch the reaction in progress.

Safety

Add these important safety precautions to your normal laboratory procedures:

- Sodium hydroxide is caustic and should be handled with special care. In case of contact with your skin, wash off the sodium hydroxide with a large amount of water.

- Crystal violet will stain skin and clothing, so be cautious in handling.

Getting Your Brain in Gear

1. Fill in the *y*-axis label that will result in a linear relationship for each order of reaction.

2. The compound *crystal violet* has a purple color in an aqueous solution. When it reacts with sodium hydroxide, crystal violet fades to colorless.

$$C_{25}H_{30}N_3Cl(aq) \quad + OH^-(aq) \rightarrow \quad (C_{25}H_{30}N_3Cl)OH^-(aq)$$

(Purple)   (Colorless)

a. What sensor could we use to measure the concentration of the crystal violet over time?

A colorimeter can measure the change in color, which can be related to the change in concentration.

b. The reaction requires much more sodium hydroxide than crystal violet to react in a reasonable amount of time. The sodium hydroxide solution to be used is about 50,000 times more concentrated than the crystal violet solution. Even if all of the crystal violet is consumed, will the sodium hydroxide concentration change much?

Because there is so much more sodium hydroxide than crystal violet, the sodium hydroxide concentration will change very little.

c. If the sodium hydroxide concentration does not change much, what will the reaction order with respect to sodium hydroxide be?

Zero. A zero-order reaction is one in which the rate is independent of the concentration of reactants.

3. The crystal violet compound is, as the name suggests, a dark blue-purple color in solution. Its absorbance at 565 nm is shown below as a function of concentration.

Optical absorption of crystal violet at 565 nm
(pathlength = 1.65 cm)

$y = 141{,}000x + 0.0211$
$R^2 = 0.9984$
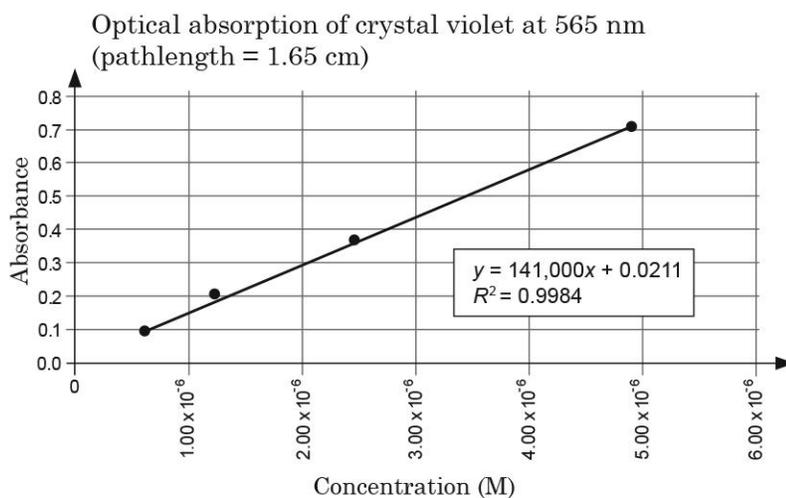
a. Why was 565 nm (green) light chosen to measure the absorbance?

Purple solutions will strongly absorb green light. Refer students to the Light, Color, and Concentration lab for more information about this relationship.

b. Just using the graph, if you measure the absorbance of a solution to be 0.3, what is the concentration of crystal violet?

2.00×10^{-6} M

c. Use the line of best fit to write an equation relating concentration and absorbance.

NOTE: The equation of the line of best fit is shown in the graph.

Absorbance = 141,000 × Concentration + 0.0211

d. Solve this equation for the concentration.

$$\text{Concentration} = \frac{(\text{Absorbance} - 0.0211)}{141{,}000}$$

e. If the absorbance was found to be 0.95, what is the concentration of crystal violet?

$$\text{Concentration} = \frac{(0.95 - 0.0211)}{141{,}000} = 6.6 \times 10^{-6} \text{ M}$$

MODEL 1

Building Model 1 – Collecting Kinetics Data

1. Connect the colorimeter to the data collection system.

2. Rinse a cuvette with distilled water and wipe any marks or fingerprints off the outside.

3. To calibrate the colorimeter, fill a cuvette 3/4 full with distilled water and place this in the colorimeter. Push the green oval button on the colorimeter. The button will light up green for several seconds. When the light goes off, make sure that all of the transmittance values have changed to 100% and the absorbance values have changed to 0.00. Repeat the process if needed.

   NOTE: This step tells the colorimeter to record this solution as having zero absorbance. You do not need to repeat this step unless the data collection interface turns off before you collect your data.

4. Obtain two 10 mL volumetric pipets. Pipet 10.00 mL of the crystal violet solution into a test tube and 10.00 mL of 0.20 M NaOH solution into a second test tube.

5. Read this entire step completely before you carry it out.

   a. Pour the crystal violet and sodium hydroxide solutions into a 50-mL beaker and swirl for 5 seconds or until the solution appears homogeneous.

   b. Fill the cuvette about 3/4 full with this solution and cap it. Place it in the colorimeter and start data collection. Collect the data for 3 minutes.

6. Sketch the absorbance versus time data on the Model 1 Graph.

NOTE: You will be using the equipment and the reaction data to make additional calculations, so don't put it away yet.

Model 1 – Collecting Kinetics Data

Model 1 Graph for the crystal violet and sodium hydroxide reaction
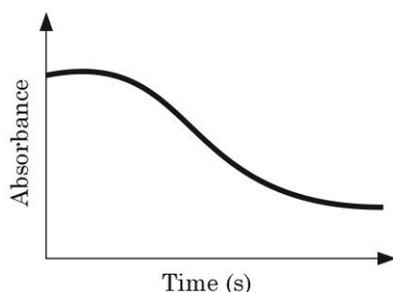
Table 1: Model 1 Data Table—Determining the order of reaction

Time (s)	Absorbance Green (565 nm)	Concentration (M) (a)	ln(Concentration) (b)	1/Concentration (c)
0	3.000	2.1×10^{-05}	−10.7	4.7×10^4
10	2.709	1.9×10^{-05}	−10.8	5.2×10^4
20	2.709	1.9×10^{-05}	−10.8	5.2×10^4
30	2.407	1.7×10^{-05}	−10.9	5.9×10^4
40	2.163	1.5×10^{-05}	−11.1	6.5×10^4
50	1.929	1.3×10^{-05}	−11.2	7.3×10^4
60	1.707	1.2×10^{-05}	−11.3	8.3×10^4
70	1.503	1.1×10^{-05}	−11.4	9.4×10^4
80	1.327	9.4×10^{-06}	−11.6	1.1×10^5
90	1.176	8.3×10^{-06}	−11.7	1.2×10^5
100	1.049	7.4×10^{-06}	−11.8	1.3×10^5
110	0.930	6.4×10^{-06}	−12.0	$1,6 \times 10^5$
120	0.847	6.0×10^{-06}	−12.0	1.7×10^5
130	0.765	5.4×10^{-06}	−12.1	1.8×10^5
140	0.696	4.9×10^{-06}	−12.2	2.0×10^5
150	0.637	4.5×10^{-06}	−12.3	2.2×10^5
160	0.588	4.2×10^{-06}	−12.4	2.4×10^5
170	0.546	3.9×10^{-06}	−12.5	2.6×10^5
180	0.510	3.9×10^{-06}	−12.5	2.6×10^5

Analyzing Model 1 – Collecting Kinetics Data

7. Using the Calculated Data menu on your data collection system, calculate the concentration of crystal violet from the green absorbance. Remember, you must input this as an equation, "concentration = … "

    NOTE: If you are not sure which equation to use, look back at your answer to the Getting Your Brain in Gear questions that relates the concentration of crystal violet to absorbance.

    For the sample data,

    $$\text{Concentration} = \frac{(\text{Absorbance} - 0.0211)}{141,000}$$

    The absorbance at t = 10 s is 2.709, so

    $$\text{Concentration} = \frac{(2.709 - 0.0211)}{141,000}$$

    Concentration = 1.9×10^{-5} M

8. Sketch or attach a copy of your graph of concentration (call this *a*) versus time and record or attach the values in the Model 1 Data Table. Can you, by visual inspection alone, determine the order of the reaction? Why or why not?

    No. The change of the crystal violet concentration resulting from the reaction is not linear (it is not zero order).

Concentration vs Time

$y = -1 \times 10^{-7}x + 2 \times 10^{-5}$
$R^2 = 0.9358$
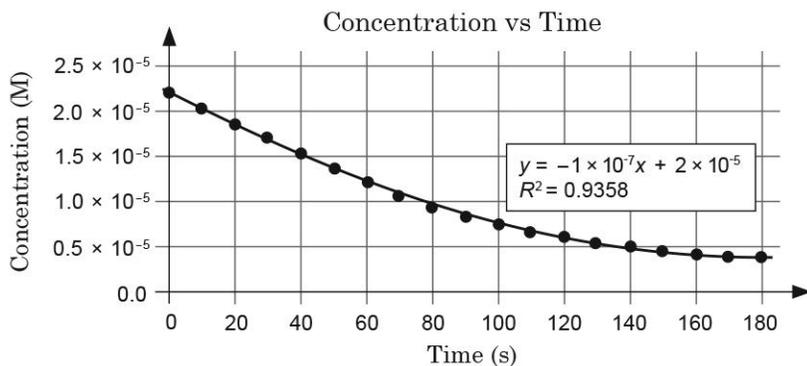
9. Using the Calculated Data menu, calculate the natural log (ln) of the concentration (call this *b*) and the inverse of the concentration (1/Concentration). Call this *c*. Record or attach the values for *b* and *c* in the Model 1 Data Table.

    Refer to the Model 1 Data Table for sample data.

10. Graph the ln(concentration) versus time. Does this appear to be a straight line?

    NOTE: Add a line of best fit and use the R² value (coefficient of determination) to determine which curve is the most linear, indicated by the value closest to one.

ln(Concentration) vs Time

$y = -0.0106x - 10.722$
$R^2 = 0.9921$
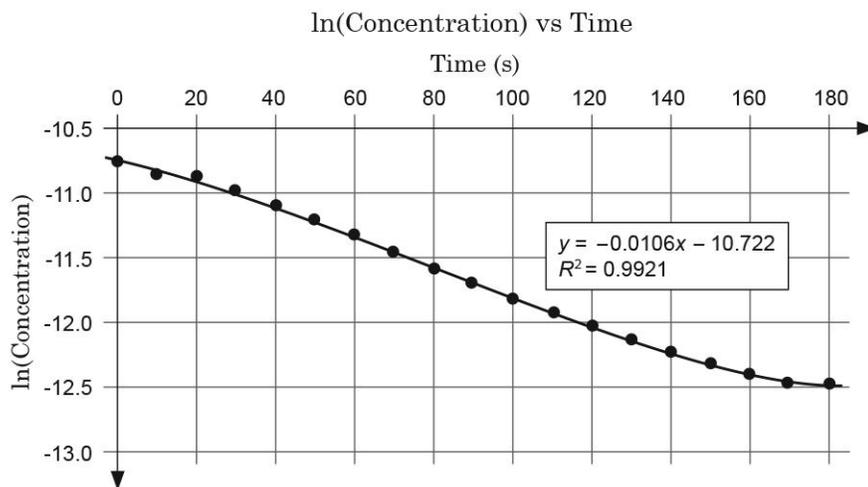
This line should appear the straightest.

11. Graph the inverse of the concentration versus time. Does this appear to be a straight line?

1/(Concentration) vs Time

$y = 1348.1x + 17321$
$R^2 = 0.9634$
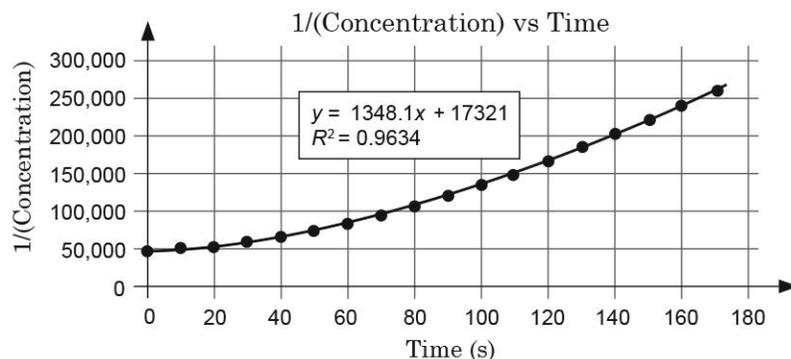
This may appear to be the straightest line, depending on how fast students managed to get their solutions in their cuvettes.

12. Based on the line of best fit, what is the value of the rate constant k for this reaction?

Based on the equation shown on the graph, the value of k (equal to the slope of the line of best fit) is -0.0106 s^{-1}.

13. Based on your answer to the previous question, write the integrated rate law for the crystal violet (CV) + sodium hydroxide reaction.

$\ln[CV] = -kt + \ln[CV]_0$

$\ln[CV] = -0.0106$ s^{-1} $t + \ln[CV]_0$

It is not uncommon for some students to determine the reaction was 2nd order, depending on how quickly they managed to get the solutions in the cuvettes.

14. Based on your equation and the value of k, at what time after the reaction started would the concentration drop from the initial concentration of 5.0×10^{-6} M to 5.0×10^{-7} M?

Answers will vary depending on students' value of k. For the sample data,

$\ln(5.0 \times 10^{-7}) = -(0.0106$ s$^{-1})(t) + \ln(5.0 \times 10^{-6})$

$t = (\ln(5.0 \times 10^{-7}) - \ln(5.0 \times 10^{-6})) / (-0.0106$ s$^{-1})$

$t = 217$ seconds (almost 4 minutes)

15. How does temperature affect the rate of a reaction? Does the temperature of the experiment appear in the integrated rate law?

Increasing the temperature increases the reaction rate. Temperature does not appear in the integrated rate law.

MODEL 2

Building Model 2 – Testing the Effect of Temperature on the Rate Constant

In this model, create an experiment in which you determine if the rate law and rate constant are affected by the temperature.

A few things to think about: What are appropriate (and safe) temperatures to use? Will using temperatures 10 °C apart be sufficient to tell if there is an effect? Will your data be more definitive if you choose a larger temperature range or a shorter range? How will you raise or lower the temperature of your solution from room temperature? How will you know the temperature of your solutions?

Conduct measurements using at least two different temperatures.

Collect and analyze the data on the data collection system. When you finish, draw sketches of your most linear graphs that show how the rate law and rate constant are affected by temperature.

Model 2 – Testing the Effect of Temperature on the Rate Constant

Model 2 Graphs of reactions carried out at different temperatures

ln(Concentration) vs Time
Temperature = 4.0 °C

$y = -0.0037x - 13.411$
$R^2 = 0.9992$

ln(Concentration) vs Time
Temperature = 55.0 °C

$y = -0.026x - 14.241$
$R^2 = 0.9888$
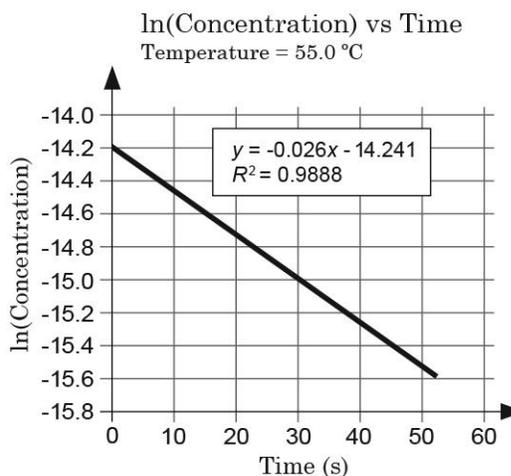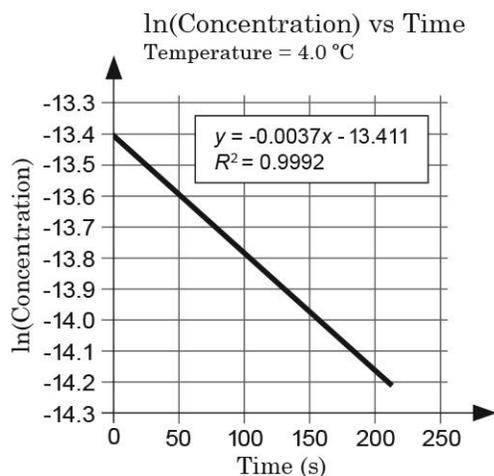
Analyzing Model 2

1. Which temperature caused the fastest reaction?

   The highest temperature resulted in the fastest reaction.

2. Which temperature produced the greatest slope?

   The reaction at the highest temperature had the greatest slope.

3. What is the rate law constant for each temperature?

   For 4.0 °C, $k = -0.0037$ and for 55.0 °C, $k = -0.026$

4. Is the rate constant affected by temperature?

   Based on our results, temperature does affect the rate constant.

Connecting to Theory

Svante Arrhenius suggested that chemical reactions need a certain amount of energy to get started. This energy is required to break bonds and align particles so that they are in the proper orientation for new bonds to form in the products. This energy is called the *activation energy* and is symbolized as E_a.

He realized that to calculate the Activation Energy, the reaction would have to be performed at two different temperatures, T. It would also require two rate constants, k_1 *and* k_2 that corresponds to the temperatures. His equation is listed below.

$$\ln\left(\frac{k_2}{k_1}\right) = \left(\frac{E_a}{R}\right)\left(\frac{1}{T_1} - \frac{1}{T_2}\right)$$

The R in the equation is the gas constant, $8.31\dfrac{J}{K\,mol}$. Calculate the activation energy from your data in Model 2.

From the sample data,

$$\ln\left(\frac{-0.026}{-0.0037}\right) = \left|\frac{E_a}{8.31\frac{J}{K\,mol}}\right|\left(\frac{1}{277\,K} - \frac{1}{328\,K}\right)$$

E_a = 28864.6 J = 28.9 kJ/mol

Applying Your Knowledge

Consider the redox reaction between potassium permanganate and sodium oxalate. The net ionic reaction is

$$2MnO_4^-(aq) + 5C_2O_4^-(aq) + 16H^+(aq) \rightarrow 2Mn^{2+}(aq) + 8H_2O(l) + 10CO_2(g)$$
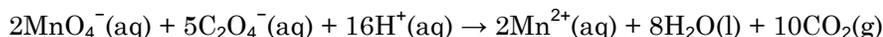
This reaction is used to titrate for oxalate, but for that purpose it is conducted at 60 °C, where it reacts very quickly. At room temperature the reaction is slow and the kinetics can be measured. However, the potassium permanganate is too dark at the relevant concentrations to measure the reaction progression with colorimetry. Suggest what sensor (or sensors) you might use instead to measure this reaction. What might the data you collect from that sensor look like?

The oxygen reduction potential (ORP) sensor or the gas pressure sensor are the best candidates, although possibly the pH or conductivity sensors could be used. The ORP sensor data would look like:
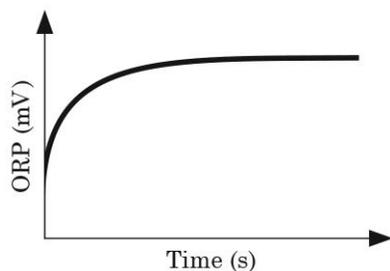
The gas pressure data would look similar. Normally the concentration of a reactant is being monitored, which is, of course, consumed. Notice here that the gas is being generated, so the graph will appears backward from what we normally see.

Teacher Tips

Tip 1 – Alternative data collection

If you wish for students to get a feel for doing the data analysis by hand, you can have them collect measurements every 10 seconds for 180 seconds, then read the data off the table and calculate the concentration, the natural log of concentration, and the inverse of concentration by hand, though this can be very time consuming for the student.

Tip 2 – First versus second order

Depending on how quickly the students have gotten their solution into the cuvette, some students may observe the reaction to be second order.

Tip 3 – Solution storage

The crystal violet stock solution stores well, so you should only need to make the stock every two or three years.

11. ENERGY IN CHEMICAL REACTIONS

Initial Question

The First Law of Thermodynamics states that energy is neither lost nor gained in a chemical process. This is paraphrased as "energy is conserved." Reactions that release energy are known as exothermic reactions. Reactions that absorb energy are endothermic reactions.

The amount of heat energy involved in a process is referred to as *enthalpy*. Although the amount of enthalpy cannot be measured directly, scientists can determine how much it changes. In this lab, you will use the First Law of Thermodynamics to determine the change of energy in various reactions and combine the results to determine the enthalpy change of a related reaction.

How do you find the change of enthalpy in chemical reactions?

Learning Objectives[*]

Students demonstrate that the heat q is dependent on reaction conditions but the change in enthalpy ΔH is a constant quantity. They will also discover and employ the additive nature of ΔH.

LO 5.7 / The student is able to design and/or interpret the results of an experiment in which calorimetry is used to determine the change in enthalpy of a chemical process (heating/cooling, phase transition, or chemical reaction) at constant pressure.

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

Time Requirement

Preparation time: 15 minutes / Lab activity: 80 minutes

Materials and Equipment

Calorimeter for Model 1, Model 2, Model 3, and Applying Your Knowledge
- Data collection system
- Stainless steel temperature sensor[1]
- Polystyrene cup, 8 oz
- Ring stand
- Beaker, 250-mL
- Clamp, utility
- Graduated cylinder, 50-mL or 100-mL
- 10 cm × 10 cm cardboard lid

[1]Included with PASCO Advanced Chemistry Sensor.

Model 1
- Ammonium nitrate (NH_4NO_3), solid[1]
- Distilled water[1]

[1]The mass (either 2.00, 4.00, or 6.00 g) and volume (50.0 mL or 100.0 mL) needed depend on the reaction assigned to the student or group.

Model 2
- 1.0 M Sodium hydroxide (NaOH), 100 mL[1]
- 1.0 M Hydrochloric acid (HCl), 100 mL[1]
- Distilled water, 100.0 mL

[1]To prepare the solutions using NaOH and 12 M HCl refer, to the Lab Preparation section.

Model 3

• 1.0 M Sodium hydroxide (NaOH), 100 mL[1,2]   • Sodium hydroxide (NaOH), 4.0 g

• 1.0 M Hydrochloric acid (HCl), 100 mL[1,2]

[1]To prepare the solutions using NaOH and12 M HCl, refer to the Lab Preparation section.

[2]The solution and volume needed depend on the reaction assigned to the student or group.

Applying Your Knowledge

• 2.0 M Hydrochloric acid (HCl), 100 mL[1]   • Magnesium ribbon (Mg), about 0.5 g

[1]To prepare the solutions using NaOH and 12 M HCl, refer to the Lab Preparation section.

Prerequisites

Students should be familiar with the following concepts:

• Stoichiometric calculations

• First Law of Thermodynamics

• Balancing chemical equations

• Endothermic and exothermic reactions

• Enthalpy

Lab Preparation

These are the materials and equipment to set up prior to the lab:

NOTE: In each model, several reactions are to be carried out. Assign one reaction to each student group so all reactions are carried out in each model. Students share the data to the reactions they haven't done.

Model 1 and Model 2

1. **1.0 M Sodium hydroxide**: Prepare 1000 mL of 1.0 M sodium hydroxide (NaOH) by placing 39.99 g of solid NaOH in a 1000-mL volumetric flask 1/3 full of distilled water. Stir it well and let it sit to cool. When the solid has completely dissolved, fill the flask to the line with distilled water.

2. **1.0 M Hydrochloric acid**: To prepare 1000 mL of 1.0 M hydrochloric acid (HCl), fill a 1000-mL volumetric flask 1/3 full of distilled water. Add 83.33 mL of 12 M HCl to the flask and swirl to dissolve. Fill the flask to the line with distilled water.

Applying Your Knowledge

3. **2.0 M Hydrochloric acid**: To prepare 1000 mL of 2.00 M hydrochloric acid, fill a 1000-mL volumetric flask 1/3 full of distilled water. Add 166.66 mL of 12 M HCl to the flask and swirl to dissolve. Fill the flask to the line with distilled water.

Safety

Add these important safety precautions to your normal laboratory procedures:

• Do not touch the solid NaOH and handle its resulting solution with care. NaOH is caustic and will cause skin burns and burn holes in clothing.

• When NaOH or HCl solutions come in contact with your skin or eyes, rinse immediately with a large amount of running water.

Getting Your Brain in Gear

1. A coffee cup calorimeter will be used to measure the heat of reaction (enthalpy of reaction) of several different reactions. The coffee cup minimizes, but does not eliminate, heat transfer with the surroundings. If the temperature of the room was 22.00 °C on the day of the experiment, what transfer of heat will take place between the solution and room, based on the temperature of the solution?

   If the temperature of the solution is lower than the temperature of the room, the solution will gain heat from the room. If it is higher than the temperature of the room, the solution will lose heat to the room.

2. Samples of solid ammonium nitrate and sodium hydroxide are depicted below.

   a. Draw the changes that take place when the following compounds dissolve in water.
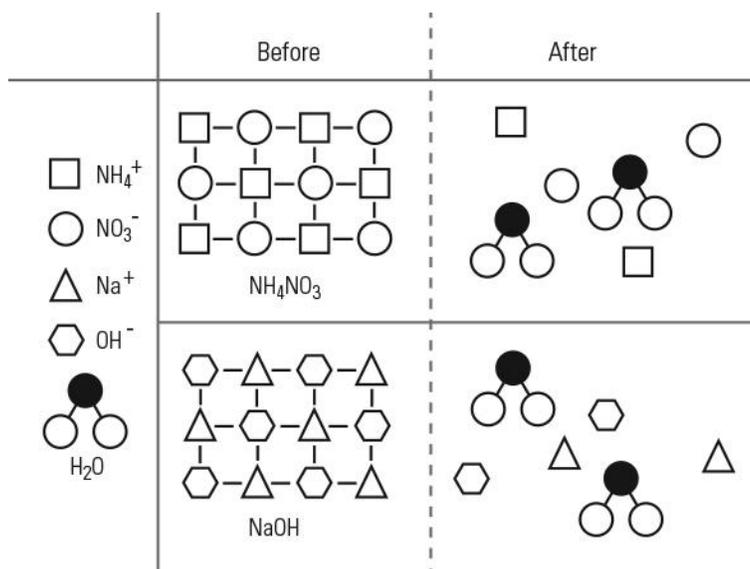
   b) Describe the changes to the intramolecular forces holding the components together when each salt is dissolved in water.

   The forces holding the particles together are overcome by the solute–solvent forces so the salts dissolve.

3. The reaction below is exothermic. What must be true about the total energy in the bonds of the reactants as compared to the total energy of the bonds in water? The formula for the *heat of reaction* is $\Delta H_{rxn} = \Sigma \Delta H_{products} - \Sigma \Delta H_{reactants}$.

$$2H_2 \text{ (g)} + O_2 \text{ (g)} \rightarrow 2H_2O \text{ (l)} \qquad \Delta H = -285.8 \text{ kJ}$$
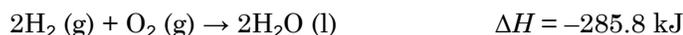
   The bonds of the product are much lower in energy than the bonds of the reactants.

4. In science, there is no such thing as negative energy but when we calculate the heat energy absorbed or released by a chemical reaction using the equation $q = mc\Delta T$, the temperature change is calculated as $T_{final} - T_{initial}$. When a chemical reaction causes a solution to cool, the change in temperature is negative ($T_{final} < T_{initial}$) and the resulting value of q is negative. q is assigned an artificial negative sign to force a relationship with ΔH. What is the relationship between the algebraic sign of q and the algebraic sign of ΔH?

   q has the opposite algebraic sign than that of ΔH.

   When q is negative, ΔH is positive and the reaction is endothermic.

   When q is positive, ΔH is negative and the reaction is exothermic.

MODEL 1

Building Model 1 – Dissolution of NH_4NO_3

1. Start a new experiment on the data collection system.

2. Connect a temperature sensor to the data collection system.

3. Create a graph display of temperature (°C) versus time (s).

4. Place the polystyrene cup in the 250-mL beaker.

5. Mount the temperature sensor on the ring stand and set it into the cup so it is about half an inch from the bottom.
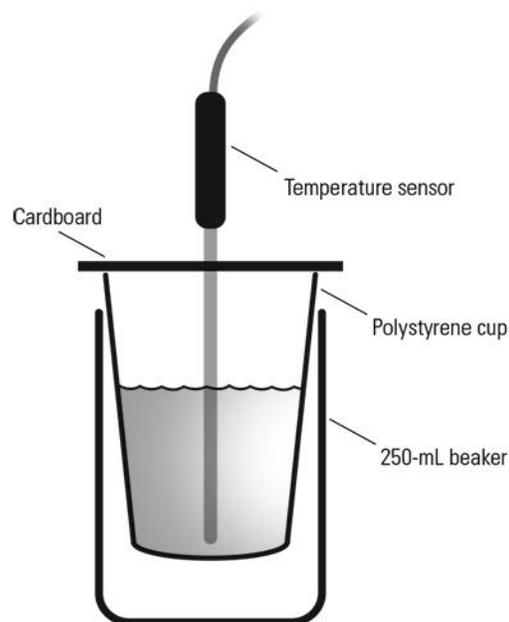
❷ 6. How will placing the cup in a beaker help improve the accuracy of temperature measurements?

   The air trapped between the wall of the cup and the beaker serves as heat insulation to lessen the heat loss.

7. Check with your teacher to determine which reaction you will carry out.

Table 1: Reactant volumes for Model 1 reactions

Reaction	Mass of NH_4NO_3 (g)	Volume of Water (mL)
A	2.00	50.0
B	2.00	100.0
C	4.00	50.0
D	4.00	100.0
E	6.00	50.0
F	6.00	100.0

8. Rinse the graduated cylinder with deionized water.

9. Measure the amount of water specified in Table 1 for your reaction. Record the volume in the Model 1 Data Table and then pour the water into the calorimeter.

10. Measure the solid reactant and record the mass to at least the nearest 0.01 g in the Model 1 Data Table.

11. Start recording data.

12. When the temperature readings stabilize, carefully transfer the solid reactant into the calorimeter. Swirl the calorimeter gently to stir.

13. When the temperature readings stabilize again, stop recording data.

14. Dispose of the solution properly, wash the cup and graduated cylinder, and rinse them with deionized water.

15. Repeat the procedure to verify your result.

16. Determine the temperature change for each data run and record it in the Model 1 Data Table.

17. Save your experiment and clean up according to your teacher's instructions. Then exchange data with your classmates and enter it into the Model 1 Data Table.

Model 1 – Dissolution of NH$_4$NO$_3$

Table 2: Model 1 Data Table—Determining the heat of reaction for the dissolution of NH$_4$NO$_3$

Reaction		Mass of NH$_4$NO$_3$ (g)	Volume of Water (mL)	ΔT (°C)	Heat q Gained or Lost, (kJ)	Number of Moles of NH$_4$NO$_3$ (mol)	ΔH$_{rxn}$ (kJ/mol)	Average ΔH$_{rxn}$ (kJ/mol)
A	Run 1	2.0200	49.9	−3.0	−0.65	0.025236	26	25
	Run 2	2.0011	49.1	−2.7	−0.58	0.025000	23	
B	Run 1	2.0129	100.1	−1.2	−0.51	0.025148	20.	23
	Run 2	2.0206	99.8	−1.5	−0.63	0.025244	25	
C	Run 1	4.0812	50.1	−5.3	−1.20	0.050988	24	24
	Run 2	4.0502	49.9	−5.3	−1.20	0.050600	24	
D	Run 1	3.9985	99.9	−2.8	−1.22	0.049954	24	25
	Run 2	3.9841	99.1	−2.9	−1.25	0.049774	25	
E	Run 1	6.0777	49.8	−7.6	−1.78	0.075930	23	23
	Run 2	6.0102	50.0	−7.4	−1.73	0.075086	23	
F	Run 1	5.9977	100.0	−4.4	−1.95	0.074931	26	26
	Run 2	6.0569	98.5	−4.3	−1.88	0.075670	25	

Analyzing Model 1 – Dissolution of NH$_4$NO$_3$

18. Describe what happened to the temperature of the solution as you increased the mass of ammonium nitrate and used the same quantity of water (Reactions A, C, and E, or B, D, and F).

    The temperature became colder as the mass of ammonium nitrate increased.

19. For each reaction, use the specific heat capacity of water to determine the heat of reaction, as follows:

    a. Calculate the heat gained by or lost to the solution using the equation $q = mc\Delta T$ where m is the mass of water plus the mass of the solute and for simplicity assume the mass of 1.00 mL of water is 1.00 g, c is the specific heat capacity of water, 4.184 J/g °C, and $\Delta T_{water} = T_{final} - T_{initial}$. Record your answer, in kilojoules, in the Model 1 Data Table.

    Example calculation for Reaction A, Run 1:

    $q = mc\Delta T$

    $q = (2.0200 \text{ g} + 49.9 \text{ g}) \times 4.184 \dfrac{J}{g \text{ °C}} \times (-3.0 \text{ °C}) \times \dfrac{1 \text{ kJ}}{1000 \text{ J}} = -0.65 \text{ kJ}$

b. Using the mass of ammonium nitrate, calculate the number of moles of ammonium nitrate present in each reaction.

Example calculation for Reaction A, Run 1:

$$\frac{2.0200 \text{ g NH}_4\text{NO}_3}{1} \times \frac{1 \text{ mol NH}_4\text{NO}_3}{80.043 \text{ g NH}_4\text{NO}_3} = 0.025236 \text{ mol NH}_4\text{NO}_3$$

Answers will vary based on student results. Refer to the Model 1 Data Table for sample data.

c. Using the number of moles of ammonium nitrate and the heat released or absorbed, calculate the heat of reaction [$\Delta H = -(q/\text{mole of product})$] for the dissolution of one mole of ammonium nitrate.

$$\Delta H = -\left(\frac{-0.65 \text{ kJ}}{0.025236 \text{ mol}}\right) = 26\frac{\text{kJ}}{\text{mol}}$$

Answers will vary based on student results. Refer to the Model 1 Data Table for sample data.

20. Will energy appear as a reactant or a product in the following equation? Write the word "energy" on the appropriate side. Explain your reasoning.

$$\text{NH}_4\text{NO}_3(\text{s}) + \text{water} \rightarrow \text{NH}_4{}^+(\text{aq}) + \text{NO}_3{}^-(\text{aq})$$
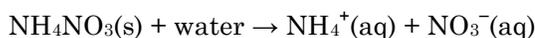
The reaction is endothermic, so energy appears as a reactant: Energy + $\text{NH}_4\text{NO}_3(\text{s})$ + water → $\text{NH}_4{}^+(\text{aq})$ + $\text{NO}_3{}^-(\text{aq})$

21. Considering the ratios of solute to solvent in Model 1, do large ratios of solute-to-solvent or small ratios of solute-to-solvent cause the greatest temperature changes? Use experimental results to support your answer.

The greatest temperature change occurs with a large amount of solute and a small amount of solvent. Reaction E required the greatest amount of solute (6 gm) and the least amount of solvent (50 mL) and showed the greatest temperature change (avg: –7.5 $^\circ$C).

22. Compare the heat q and heat of reaction ΔH. What are the main differences between the two quantities?

The *heat* absorbed or liberated by the system is measured by the change in temperature of water. The *heat of reaction* refers to the total of the heat absorbed or liberated in a reaction with respect to the quantity of reactants that caused the exchange.

23. Identify and explain any trends in the heat of reaction for Model 1.

The heat of reaction is constant for a specific reaction. ΔH is the same for each trial because it is the amount of heat absorbed or liberated on a per mole basis.

24. Consider an additional reaction for Model 1 using 10 g of ammonium nitrate in 50.0 mL of water.

a. How would this mass and volume affect the change in temperature compared to the other trials?

The decrease in temperature would be greater than in the other trials.

b. Speculate on the quantity of heat q that would have been gained or lost by the solution in this reaction.

Answers will vary but the greater decrease in temperature would result in a greater decrease in the heat of the solution.

c. What effect would this have had on your calculation of the heat of reaction for Model 1?

The heat of reaction would remain the same.

Model 2

Building Model 2 – Limiting Reactants

1. Set up the calorimeter as you did for Model 1.

2. Check with your teacher to determine which reaction you will carry out.

❷ 3. What is the relationship between the amount of HCl and the amount of NaOH for the five reactions in Table 3?

Table 3: Model 2 reactions using different ratios of reactant volumes

Ratio	Reactant 1 1.0 M HCl (aq) (mL)	Reactant 2 1.0 M NaOH (aq) (mL)
1	10.0	50.0
2	20.0	40.0
3	30.0	30.0
4	40.0	20.0
5	50.0	10.0

As the HCl increases, the amount of NaOH decreases and there is always a total of 60 mL.

4. For your assigned reaction, measure the specified volume of Reactant 1. Record the value in the Model 2 Data Table and pour Reactant 1 into the calorimeter.

5. Rinse the graduated cylinder. Measure Reactant 2 and record the volume in the Model 2 Data Table.

6. Start recording data.

7. When the temperature readings stabilize, pour Reactant 2 into the calorimeter. Swirl the calorimeter gently to stir.

8. When the temperature readings stabilize again, stop recording data.

9. Dispose of the solution properly, wash the cup and graduated cylinder, and rinse them with deionized water.

10. Conduct the experiment again to obtain a second run.

11. Determine the initial and maximum temperature for each data run. Record the values in Model 2 Data Table.

12. Save your experiment and clean up according to your teacher's instructions. Then exchange data with your classmates and enter it into the Model 2 Data Table so you have the results for each reaction ratio.

Model 2– Limiting Reactants

Table 4a: Model 2 Data Table – Limiting Reactants: Measurements

Reaction		Volume (mL)		Temperature (°C)	
Ratio	Run	1.0 M HCl (aq)	1.0 M NaOH (aq)	Initial	Final
1	Run 1	9.1	49.1	26.8	28.7
1	Run 2	9.5	49.2	26.5	28.4
2	Run 1	19.9	40.5	25.3	30.1
2	Run 2	20.7	40.0	26.3	30.3
3	Run 1	31.1	29.7	24.8	30.0
3	Run 2	30.9	29.1	23.8	29.2
4	Run 1	40.0	19.9	24.2	28.4
4	Run 2	39.9	20.1	24.4	28.5
5	Run 1	50.1	9.8	24.5	26.3
5	Run 2	49.1	9.9	24.2	26.2

Table 4b: Model 2 Data Table – Limiting Reactants: Calculation of the heat of reaction

Reaction		Temperature Change ΔT (°C)	Heat q (kJ)	Number of Moles		Heat of Reaction ΔH (kJ/mol)	Average Heat of Reaction ΔH (kJ/mol)
Ratio	Run			HCl	NaOH		
1	Run 1	1.9	0.46	0.0091	0.049	–51	–50.
1	Run 2	1.9	0.47	0.0095	0.049	–49	–50.
2	Run 1	4.8	1.2	0.020	0.041	–61	–55
2	Run 2	4.0	1.0	0.021	0.040	–49	–55
3	Run 1	5.2	1.3	0.031	0.031	–43	–43
3	Run 2	5.4	1.4	0.031	0.029	–44	–43
4	Run 1	4.2	1.1	0.040	0.020	–53	–52
4	Run 2	4.1	1.0	0.040	0.020	–51	–52
5	Run 1	1.8	0.45	0.051	0.0098	–46	–47
5	Run 2	2.0	0.49	0.049	0.0099	–50.	–47

Analyzing Model 2– Limiting Reactants

13. a. What is the equation for this reaction?

    NaOH(aq) + HCl(aq) → NaCl(aq) + H$_2$O(l)
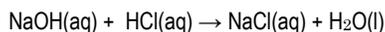
    b. Calculate the heat q absorbed or released by the solution. Record your results in the Model 2 Data Table.

    Example calculation for Ratio 1, Run 1:

    $T_{final} - T_{initial} = \Delta T$

    28.7 °C – 26.8 °C = 1.9 °C

    Determine the heat released or absorbed:

    Assuming 1.0 mL of solution = 1.0 g, $m = 9.1\,g + 49.1\,g = 58.2\,g$

    $q = mc\Delta T$

    $q = 58.2\,g \times 4.184 \dfrac{J}{g\ °C} \times \dfrac{1\,kJ}{1000\,J} \times 1.9\ °C = 0.46\,kJ$

    c. Circle the limiting reagent (the one with the least number of moles) in Table 3, copied below, for each reaction.

Ratio	Reactant 1 1.0 M HCl (aq) (mL)	Reactant 2 1.0 M NaOH (aq) (mL)
1	(10.0)	50.0
2	(20.0)	40.0
3	30.0	30.0
4	40.0	(20.0)
5	50.0	(10.0)

    d. What will happen to the reaction when you run out of limiting reactant?

    The reaction will stop.

    e. Which should you use, the number of moles of the limiting reactant or the number of moles of the excess reagent, when calculating the molar heat of reaction (kJ per mole of product)? Explain your answer.

    The number of moles of limiting reagent should be used to calculate the molar heat of reaction. That is the number of moles of product that will form in this reaction.

14. Calculate the heat of reaction ΔH as you did in Model 1, using the following steps. Record all results in the Model 2 Data Table.

    a. Calculate the number of moles of HCl and NaOH used in each reaction. How many moles of product are formed?

    Example calculation for Ratio 1, Run 1.

    $\dfrac{9.1\ mL\ HCl}{1} \times \dfrac{1\,L}{1000\ mL} \times \dfrac{1.0\ mol}{L} = 0.0091\ mol\ HCl$

    $\dfrac{49.1\ mL\ NaOH}{1} \times \dfrac{1\,L}{1000\ mL} \times \dfrac{1.0\ mol}{L} = 0.0491\ mol\ NaOH$

b. Calculate the heat of reaction ΔH.

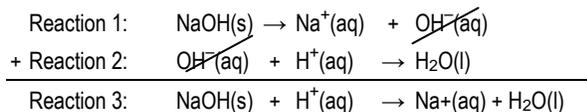Example calculation for Ratio 1, Run 1:

$$\Delta H = -\left(\frac{q}{\text{mole of product}}\right)$$

$$\Delta H = -\left(\frac{0.46 \text{ kJ}}{0.0091 \text{ mol}}\right) = -51 \frac{\text{kJ}}{\text{mol}}$$

15. Describe the changes in the heat q with respect to the ratios of reactants present.

As the ratio of reactants approached 1, the quantity of heat increased.

16. Compare your results with the results of other students with respect to the trends and values of the heat q and the molar heat of reaction, ΔH.

This is being done to ensure consistency in data; students should find that the results are close.

17. Which ratio had the least amount of leftover reactants? Explain, citing data from the experiment.

Ratio 3 had equal quantities of each reactant and therefore left no excess reactants. This is evident because this reaction produced the most heat.

18. How did the amount used of each reactant affect the heat of reaction ΔH? Why do you think this is?

The amount of reactants used does not affect the heat of reaction because the heat of reaction is calculated per mole of product; a small amount of reactant may generate a small amount of heat but when that value of heat is adjusted per mole of product, it becomes a constant.

MODEL 3

Building Model 3 – Additive Nature of Reactions

1. Set up the calorimeter as you did for the previous models.

2. Check with your teacher to determine which reaction you will carry out.

Table 5: Reactions and reactants for Model 3

Rxn #	Reactions	Reactant 1	Reactant 2
1	$NaOH(s) \rightarrow NaOH(aq)$	100.0 mL water	4.00 g NaOH
2	$NaOH(aq) + HCl(aq) \rightarrow NaCl(aq) + H_2O(l)$	100.0 mL 1.0 M HCl(aq)	100.0 mL 1.0 M NaOH(aq)
3	$NaOH(s) + HCl(aq) \rightarrow NaCl(aq) + H_2O(l)$	100.0 mL 1.0 M HCl(aq)	4.00 g NaOH

3. Rinse a graduated cylinder with deionized water and obtain Reactant 1 based on your assigned reaction.

❷ 4. Why is it important to rinse the graduated cylinder with deionized water between each use?

Rinsing will minimize the impurities introduced to the system.

5. Carefully transfer the contents of the graduated cylinder into the calorimeter.

6. Obtain Reactant 2.

NOTE: Since solid sodium hydroxide readily picks up moisture from the air, obtain its mass and proceed to the next step without delay.

7. Start recording data.

8. When the temperature readings stabilize, add Reactant 2 to the calorimeter.

9. Swirl gently to stir. When the temperature readings stabilize again, stop recording data.

❷ 10. Why is it important to wait for the readings to stabilize before adding Reactant 2?

This will indicate the baseline or starting temperature for the measurement, making the determination of the change in temperature much easier.

11. Dispose of the solutions according to your teacher's instructions, wash the cup and graduated cylinder, and rinse them with deionized water.

12. Conduct the experiment again to obtain a second run.

13. Determine the initial and maximum temperature for each data run. Record the values in the appropriate Model 3 Data Table.

14. Clean up according to your teacher's instructions. Then exchange data with your classmates and enter it into the Model 3 Data Table so you have the results for each reaction.

Model 3 – Additive Nature of Reactions

Table 6a: Model 3 Data Table—Reaction 1

Parameters	Reaction 1 $NaOH(s) \rightleftharpoons Na^+(aq) + OH^-(aq)$	
	Run 1	Run 2
Initial temperature (°C)	24.8	23.8
Final temperature (°C)	34.2	29.3
Mass of solid NaOH (g)	3.9910	4.0014
Volume of water (mL)	99.1	99.9
Mass of solution (g)	103.1	103.9
Change of temperature (°C)	9.4	5.5
Heat q (kJ)	4.1	2.4
Number of moles of NaOH (mol)	0.9978	0.1001
Molar heat of reaction ΔH (kJ/mol)	–42	–24
Average molar heat of reaction ΔH (kJ/mol)	–33	

Table 6b: Model 3 Data Table—Reaction 2

Parameters	Reaction 2 NaOH(aq) + HCl (aq) ⇌ NaCl(aq) + H₂O(l)	
	Run 1	Run 2
Initial temperature (°C)	26.8	24.4
Final temperature (°C)	32.9	31.9
Volume of 1.0 M NaOH (mL)	99.1	99.8
Volume of 1.0 M HCl (mL)	99.5	99.9
Mass of solution (g)	198.6	199.7
Change of temperature (°C)	6.1	7.5
Heat q (kJ)	5.1	6.3
Number of moles of NaOH (mol)	0.0991	0.0998
Number of moles of HCl (mol)	0.0995	0.0999
Molar heat of reaction ΔH (kJ/mol)	–51	-63
Average molar heat of reaction ΔH (kJ/mol)	–57	

Table 6c: Model 3 Data Table—Reaction 3

Parameters	Reaction 3 NaOH(s) + HCl(aq) ⇌ NaCl(aq) + H₂O(l)	
	Run 1	Run 2
Initial temperature (°C)	25.7	25.2
Final temperature (°C)	47.5	40.3
Mass of solid NaOH (g)	4.0221	3.8807
Volume of 1.0 M HCl (mL)	98.2	99.7
Mass of solution (g)	102.2	103.6
Change of temperature (°C)	21.8	15.1
Heat q (kJ)	9.3	9.4
Number of moles of NaOH (mol)	0.1006	0.0970
Number of moles of HCl (mol)	0.0982	0.0997
Molar heat of reaction ΔH (kJ/mol)	–94	–97
Average molar heat of reaction ΔH (kJ/mol)	–96	

Analyzing Model 3 – Additive Nature of Reactions

15. Calculate the change of temperature due to the reaction you carried out. Record your results in the corresponding Model 3 Data Table.

    Example calculation for Reaction 1, Run 1:

    $\Delta T = 34.2\ °C - 24.8\ °C = 9.4\ °C$

16. Calculate the heat q as you did in Model 1 and Model 2. Record your results in the corresponding Model 3 data table.

    Example calculation for Reaction 1, Run 1:

    $q = mc\Delta T$

    $q = (103.1\ \text{g H}_2\text{O}) \times (4.184\ \dfrac{\text{J}}{\text{g °C}} \times \dfrac{\text{kJ}}{1000\ \text{J}}) \times (9.4\ °C)$

    $q = 103.1\ \text{g} \times 0.004184\ \dfrac{\text{kJ}}{\text{g °C}} \times 9.4\ °C = 4.05452\ \text{kJ} \approx 4.1\ \text{kJ}$

17. Calculate the number of moles of the reactants in each reaction. Record the results in the corresponding Model 3 Data Table. What is the limiting reagent for each reaction?

    NOTE: For Reaction 2, remember that the units of molarity are moles/liter and the answer should be in moles.

    FOR REACTION 1, RUN 1

    $3.991\ \text{g NaOH} \times \dfrac{1\ \text{mol NaOH}}{39.9971\ \text{g NaOH}} = 0.09978\ \text{mol NaOH}$

    NaOH is the limiting reagent.

    FOR REACTION 2, RUN 1:

    0.0991 L × 1 mol/L NaOH = 0.0991 mol NaOH

    0.0995 L × 1 mol/L HCl = 0.0995 mol HCl

    Ideally the same number of moles of NaOH and HCl react, but in this example there is slightly less NaOH, so NaOH is the limiting reagent. The number of moles of product will be 0.0991 mol.

    FOR REACTION 3, RUN 1:

    0.0982 L × 1 mol/L HCl = 0.0982 mol HCl

    $4.0221\ \text{g NaOH} \times \dfrac{1\ \text{mol NaOH}}{39.9971\ \text{g NaOH}} = 0.1006\ \text{mol NaOH}$

    Ideally the same number of moles of NaOH and HCl react, but in this example there is slightly less HCl, so HCl is the limiting reagent. The number of moles of product will be 0.0982 mol.

18. Compare your results to the results of other students. Note similarities and differences with respect to the heat q and the molar heat of reaction ΔH.

    This is being done to ensure consistency in data; students should find that the results are close.

19. Determine the number of moles of product that will be created. Then calculate the molar change of heat ΔH for each reaction (kJ per mole of product) and indicate if the reaction was endothermic or exothermic. Record your results in Model 2 data table.

    Example calculation for Reaction 1, Run 1:

    $\Delta H = -\left(\dfrac{q}{\text{moles of product}} \right) = -\left(\dfrac{4.1\ \text{kJ}}{0.9978\ \text{mol}} \right) = -42\ \dfrac{\text{kJ}}{\text{mol}}$

    The temperature of the solution increased; the reaction was exothermic.

20. Write the net ionic equation for each of the three reactions.

Net ionic equation for Reaction 1:	$NaOH(s) \rightarrow Na^+ (aq) + OH^- (aq)$
Net ionic equation for Reaction 2:	$OH^- (aq) + H^+ (aq) \rightarrow H_2O (l)$
Net ionic equation for Reaction 3:	$NaOH (s) + H^+ (aq) \rightarrow Na^+ (aq) + H_2O (l)$

21. Demonstrate the relationship between the three ionic equations by combining them so the addition of the first two reactions equals the third. In the space below, algebraically add the ions from two of the reactions to equal the third reaction.

Reaction 1: $NaOH(s) \rightarrow Na^+(aq) + \cancel{OH^-(aq)}$

+ Reaction 2: $\cancel{OH^-(aq)} + H^+(aq) \rightarrow H_2O(l)$

Reaction 3: $NaOH(s) + H^+(aq) \rightarrow Na+(aq) + H_2O(l)$

22. By citing the heats of reaction you obtained, mathematically verify that you added the correct two reactions together.

For the sample data:

Reaction 1: $\Delta H_{rxn1} = -33$ kJ

+ Reaction 2: $\Delta H_{rxn2} = -57$ kJ

Reaction 3: $\Delta H_{rxn3} = -90$ kJ
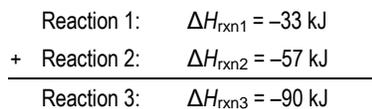
This value is close to the measured value of –96 kJ/mol.

23. The previous two questions outline fundamental points of *Hess's Law*—the additive nature of heats of reactions. Describe Hess's Law.

The net ionic equations for two reactions can be added (cancelling ions that appear in equal amounts on both sides of the arrow) to get an equation for the third reaction. The heats of reaction for each equation can also be added.

24. How would the numerical value for ΔH_{rxn} change if the calorimeter was made of a conducting material and absorbs a significant amount of energy?

In the equation, $q = mc\Delta T$, ΔT would be smaller than expected because both the solution and the calorimeter would change temperature but only the solution would be accounted for. ΔH is calculated by obtaining q/mole and since q would be less than expected, ΔH_{rxn} would be too small.

25. How would the numerical value of ΔH_{rxn} change if your lab partner put too much of the limiting reagent in the calorimeter?

In the equation, $q = mc\Delta T$, ΔT would be greater than expected because of the additional reactant. ΔH is calculated by determining q/mole of product. Since q is greater than it should be, ΔH would be too big.

Connecting to Theory

Thermochemistry studies are based on measuring the heat released or absorbed in a chemical process. The First Law of Thermodynamics states that energy is conserved in a process; therefore, any energy released or absorbed as heat can be measured by its direct effect on the environment. When a reaction is carried out in an aqueous solution, the energy given off or taken in by the process is transferred to or from the water although a small percentage may be lost to the calorimeter.

For example, if a reaction releases heat, an exothermic reaction, then the temperature of the water will increase. On the other hand, an endothermic reaction will absorb heat from the water, thus causing a decrease in the temperature of the water. This allows for a simple calculation of the heat of the reaction by first measuring the temperature change for the water, and then using the following equation to calculate the heat q absorbed or released by the dilute solution:

$$q = mc\Delta T$$

where m is the mass of the solution (assume the mass of 1.00 mL of solution is 1.00 g), c is the specific heat capacity of water: 4.184 J/g $^{\circ}$C, and $\Delta T = T_{final} - T_{initial}$ of the solution. When the solutions used are dilute, they are assumed to have the same thermal properties as water.

In the Model 3 experiment, a polystyrene-cup calorimeter was used to measure the heat released by three different reactions. One of the reactions can be expressed as the combination of the other two reactions. Therefore, the heat of reaction of the one reaction should be equal to the sum of the heats of reaction of the other two. This concept is sometimes referred to as Hess's Law, or the additivity of heats of reaction.

Applying Your Knowledge – Applying Hess's Law

The following reaction cannot be performed directly:

$$Mg + \tfrac{1}{2}O_2 \rightleftharpoons MgO$$
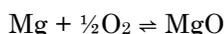
To calculate the energy of formation for magnesium oxide, Hess's Law must be applied. A pathway that can be used is:

$Mg + 2HCl \rightleftharpoons MgCl_2 + H_2$	$\Delta H_1 =$	?
$MgCl_2 + H_2O \rightleftharpoons MgO + 2HCl$	$\Delta H_2 =$	133 kJ/mol
$H_2 + \tfrac{1}{2}O_2 \rightleftharpoons H_2O$	$\Delta H_3 =$	−286 kJ/mol
$Mg + \tfrac{1}{2}O_2 \rightleftharpoons MgO$	$\Delta H_4 =$	?
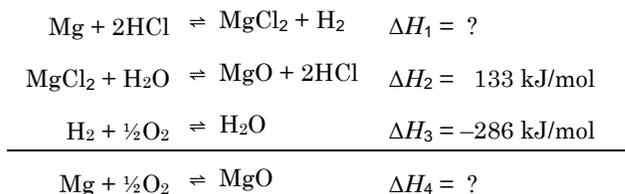
Design an experiment using approximately 0.5 g of magnesium ribbon and 2.0 M HCl to determine ΔH_1. Be sure to record the actual amounts you used in the data table. Show your process of determining the limiting reactant. Then use Hess's law to determine the energy required to form one mole of MgO. Make sure the magnesium dissolves fully.

Table 7: Determination of ΔH_1

Parameters	Reaction 1 $Mg + 2HCl \rightleftharpoons MgCl_2 + H_2$	
	Run 1	Run2
Initial temperature (°C)	23.5	26.0
Maximum temperature (°C)	66.9	62.5
Mass of solid Mg	0.4654	0.4195
Volume of 2.0 M HCl (mL)	50.0	49.1
Mass of solution (g)	50.465	49.520
Change of temperature (°C)	43.4	36.5
Heat q (kJ)	9.16	7.56
Number of moles of HCl (mol)	0.10	0.0982
Number of moles of Mg (mol)	1.92×10^{-2}	1.72×10^{-2}
Molar heat of reaction ΔH_1 (kJ/mol)	−477	−420
Avg molar heat of reaction ΔH_1 (kJ/mol)	−448	

The molar heat of reaction for the formation of MgO is ___−603 kJ/mol___ (ΔH_4).

For Run 1 sample data:

Apply $q = mc\Delta T$:

$\Delta T = (66.9\,^{\circ}C - 23.5\,^{\circ}C) = 43.4\,^{\circ}C$; the reaction is exothermic

$$q = (50.465\text{ g}) \times (4.184\frac{J}{g\,^{\circ}C} \times \frac{kJ}{1000\text{ J}}) \times (43.4\,^{\circ}C) = 9.16\text{ kJ}$$

Determine the number of moles of Mg and the number of moles of HCl used, making sure Mg was the limiting reagent:

The number of moles of HCl used:

2.00 mol/L HCl × 0.05 L = 0.10 moles HCl

The number of moles of Mg used:

$$0.4654\text{ g Mg} \times \frac{1\text{ mol}}{24.305\text{ g}} = 1.915 \times 10^{-2}\text{ mol Mg}$$

Mg is the limiting reagent, since the stoichiometric number of moles of HCl needed is 2 × (1.915 × 10⁻² mol Mg) = 3.830 × 10⁻². Sufficient HCl is being used to ensure Mg is the limiting reagent.

The heat of reaction for Reaction 1, Run 1:

$$\Delta H_1 = -\left(\frac{q}{\#\text{ moles of product}}\right) = -\left(\frac{9.16\text{ kJ}}{1.92 \times 10^{-2}}\right) = -477\frac{kJ}{mol}$$

To obtain ΔH_4:

$$\begin{aligned}\Delta H_{1,avg} &= -448\text{ kJ/mol}\\\Delta H_{2,avg} &= 133\text{ kJ/mol}\\+\quad \Delta H_{3,avg} &= -286\text{ kJ/mol}\\\hline\Delta H_4 &= -601\text{ kJ/mol}\end{aligned}$$

Compare your results to known values and calculate the percent error. The following website may be helpful: http://bilbo.chm.uri.edu/CHM112/tables/thermtable.htm.

For the sample data:

$$\text{Percent Error} = \left| \frac{\text{Theoretical Value} - \text{Experimental Value}}{\text{Theoretical Value}} \right| \times 100$$

$$\text{Percent Error} = \left| \frac{(-601.7 \text{ kJ/mol}) - (-601 \text{ kJ/mol})}{-601.7} \right| \times 100 = 0.11\%$$

Teacher Tips

Tip 1 – Calorimeter Options

Instead of using, a polystyrene cup with a cardboard top, the PASCO TD-8825A Calorimeter can be used.

Tip2 – NaOH solutions

NaOH solutions do not have good shelf lives. Make them the day before the lab.

Tip 3 – Thermal Equilibrium

Store the chemicals so they will be at thermal equilibrium. Results will be affected if one of the reactants is at a different temperature.

12. CHEMICAL EQUILIBRIUM

Initial Question

In 1901, Henry Louis Le Châtelier combined explosive hydrogen gas with nitrogen gas in an attempt to form ammonia. His efforts met with disastrous results—he almost killed his assistant. Although he abandoned the synthesis of ammonia, he had a fine career that led him to discover the principle of chemical equilibrium, now known as Le Châtelier's Principle. This principle is used by chemical engineers to create processes that make the maximum amount of products.

How can a chemical reaction be manipulated to maximize yield (without blowing up your assistant)?

Learning Objectives[*]

Students will manipulate variables to explore how to control the direction of a reversible chemical reaction.

LO 6.9 / The student is able to use Le Châtelier's principle to design a set of conditions that will optimize a desired outcome, such as product yield.

LO 6.10 / The student is able to connect Le Châtelier's principle to the comparison of Q to K by explaining the effects of the stress on Q and K.

SP 4.2 / The student can *design a plan* for collecting data to answer a particular question

Time Requirement

Preparation time: 30 minutes / Lab activity: 90 minutes

Materials and Equipment

Model 1

- Data collection system
- Colorimeter
- Extension cable[1]
- Cuvettes[1] (3)
- Beakers (3), 50-mL

- Mohr pipet, 10-mL
- Pipet bulb
- 0.0080 M Iron(III) nitrate ($Fe(NO_3)_3$), 3.0 mL[2]
- 0.0010 M Potassium thiocyanate (KSCN), 3.0 mL
- Kimwipes®

[1]Included with PASCO Colorimeter.
[2]To prepare the 0.0080 M Iron(III) nitrate using ($Fe(NO_3)_3 \cdot 9H_2O$) refer to the Lab Preparation section.

Model 2

- Test tube rack
- Distilled water, 2 mL
- Plastic pipets (3)
- Test tubes (3), 19 × 150 mm (medium)
- Gloves
- Marking pen

- Cobalt chloride ($CoCl_2$), 1.5 g[1]
- 0.10 M Silver nitrate ($AgNO_3$), 2 mL
- 6.0 M Hydrochloric acid (HCl), 2 mL
- Scoop
- Glass stirring rod

[1]Provide students with cobalt chloride hexahydrate ($CoCl_2 \cdot 6H_2O$).

Model 3

- Data collection system
- Fast-response temperature sensor
- Beakers(2), 250-mL
- Hot plate

- Cobalt solution from Model 2
- Water for water baths
- Ice

Applying Your Knowledge

- Data collection system
- Colorimeter
- Extension cable[1]
- Cuvettes[1]
- Mohr pipet, 10-mL
- Pipet bulb

- Equipment and amounts depend on the procedure:
  Test tube, 19 × 150 mm (medium)
  Beakers, 50-mL
  Graduated cylinder, 10-mL
  0.0010 M Potassium thiocyanate (KSCN)
  0.0080 M Iron(III) nitrate $(Fe(NO_3)_3)$[2]
- Kimwipes®

[1]Included with PASCO Colorimeter.
[2]To prepare the 0.0080 M Iron(III) nitrate using $(Fe(NO_3)_3 \cdot 9H_2O)$ refer to the Lab Preparation section.

Prerequisites

Students should be familiar with the following concepts:

- Equilibrium
- Equilibrium calculations, K_c
- The basics of Le Châtelier's Principle
- Conditional Reaction Quotient, Q
- Procedures of the Light, Color, and Concentration lab activity

Lab Preparation

These are the materials and equipment to set up prior to the lab:

Model 1 and Applying Your Knowledge

1. **0.0080 M Iron(III) nitrate**: To prepare 1000 mL of 0.0080 M iron(III) nitrate nonahydrate $(Fe(NO_3)_3 \cdot 9H_2O)$, fill a 1000-mL volumetric flask 1/3 full of distilled water. Add 3.232 g of iron(III)nitrate nonahydrate to the flask and swirl to dissolve. Fill the flask to the mark with distilled water.

2. **0.0030 M Potassium thiocyanate stock solution :** To prepare 1000 mL of 0.0030 M potassium thiocyanate (KSCN), fill a 1000-mL volumetric flask 1/3 full of distilled water. Add 0.292 g of potassium thiocyanate to the flask and swirl to dissolve. Fill the flask to the mark with distilled water.

   a. **0.0010 M Potassium thiocyanate:** As this solution is too dilute to create directly, prepare 1000 mL of 0.0010 M potassium thiocyanate (KSCN), by filling a 1000-mL volumetric flask 1/3 full of distilled water. Add 333.3 mL of the 0.0030 M potassium thiocyanate stock solution to the flask and swirl to dissolve. Fill the flask to the mark with distilled water.

Model 2

3. **6.0 M Hydrochloric acid:** This dilution is exothermic; add the acid in small increments, allowing the solution to cool between increments. To prepare 1000 mL of 6.0 M hydrochloric acid (HCl), fill a 1000-mL volumetric flask 1/3 full of distilled water. Add 500.00 mL of concentrated hydrochloric acid to the flask and swirl to dissolve. Fill the flask to the mark with distilled water.

4. **0.10 M Silver nitrate:** To prepare 500 mL of 0.10 M silver nitrate (AgNO$_3$) fill a 1000-mL volumetric flask 1/3 full of distilled water. Add 16.987 g of silver nitrate to the flask and swirl to dissolve. Fill the flask to the mark with distilled water.

Safety

Add these important safety precautions to your normal laboratory procedures:

• Hydrochloric acid is corrosive. If you come in contact with it, flush the area with plenty of water. It can cause severe tissue burns.

• Cobalt solutions are moderately toxic and are body tissue irritants. If you come in contact with it, flush the area with plenty of water.

• Silver nitrate will stain skin and clothing. Wear gloves when you work with it. If you do come in contact with it, flush the area with plenty of water.

Getting Your Brain in Gear

1. Consider the following equilibrium system:

$$A(aq) \rightleftharpoons B(aq)$$
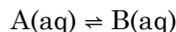
a. Write the equilibrium expression for this system.

$$K_c = \frac{[B]}{[A]}$$

b. If the value of K_c is 2, what is the ratio of the [A] to the [B]?

The ratio of the [A]:[B] is 1:2.

c. Which picture(s) represent the system at equilibrium?
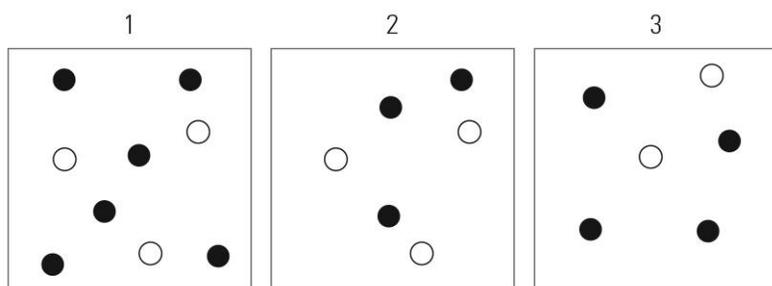
Boxes I and III represent the correct ratio for equilibrium.

d. Is there a single set of data for [A] and [B] that satisfies the equilibrium state?

No.

2. Consider the following system:

$$Co(H_2O)_6^{2+}(aq) \ + 4Cl^-(aq) \ \rightleftharpoons 6H_2O(l) + \ CoCl_4^{2-}(aq)$$

$$\text{Pink} \qquad\qquad\qquad\qquad\qquad \text{Blue}$$
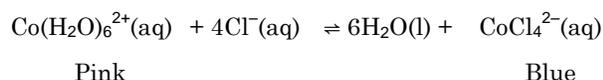
a. Write the equilibrium expression for this system.

$$K_c = \frac{\left[CoCl_4^{-2}\right]}{\left[Co(H_2O)_6^{+2}\right]\left[Cl^-\right]^4}$$

b. The reaction quotient Q expresses the relative ratio of products to reactants at a given instant. Write the reaction quotient expression for this system.

$$Q = \frac{\left[CoCl_4^{-2}\right]}{\left[Co(H_2O)_6^{+2}\right]\left[Cl^-\right]^4}$$

3. How is an equilibrium constant different from a reaction quotient?

Although the calculations look the same, the equilibrium constant represents the ratio of concentrations of products to reactants at equilibrium, whereas a reaction quotient is a ratio of concentrations that may or may not be at equilibrium.

4. When does the value of $Q = K_c$?

They are equal when the system is at equilibrium.

5. Explain the following statement: At constant temperature, there is only one equilibrium constant for a system but many different equilibrium states or positions. Provide three examples of product and reactant concentrations that will give $K_c = 20$.

    The products and reactants rearrange until their quotient becomes equal to the equilibrium constant. Examples will vary but they should all show a ratio of $K_c = 20/1$, for example, $K_c = 100/5$ and $K_c = 10/0.5$.

6. Label the following reactions as either endothermic or exothermic:

    heat $+ A \rightleftharpoons B$ endothermic

    $A \rightleftharpoons B +$ heat   exothermic
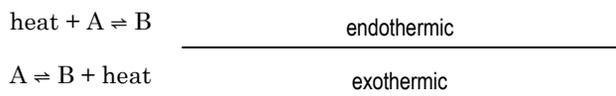
MODEL 1

Building Model 1 – K_c as a Constant

When iron(III) nitrate ($Fe(NO_3)_3$) and potassium thiocyanate (KSCN) solutions react, the following equilibrium is created:
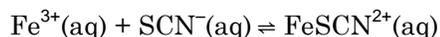
$$Fe^{3+}(aq) + SCN^-(aq) \rightleftharpoons FeSCN^{2+}(aq)$$

1. Start a new experiment on the data collection system.

2. Connect the colorimeter to the data collection system using the extension cable.

3. Fill a cuvette at least ¾ full with distilled water.

4. Wipe off the sides of the cuvette with a lint free tissue and only handle it by the top.

5. Calibrate the colorimeter with the distilled water. The water sample is called a *blank*.
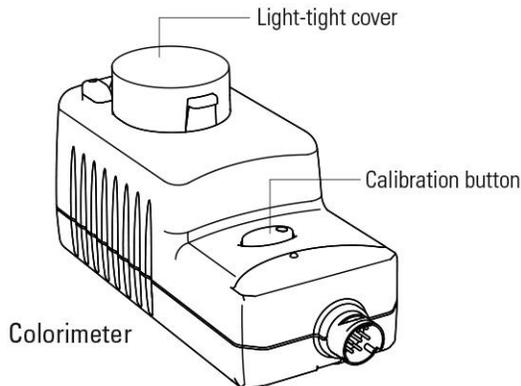
6. Place 3.0 mL of 0.0080 M iron(III) nitrate and 3 mL of 0.00100 M potassium thiocyanate into separate 50-mL beakers. Record the molarity, volume, and color of the solutions in the Model 1 Data Table—Before reacting.

7. Pour the solutions into a third 50-mL beaker and swirl gently to mix thoroughly. Then pour the solution into a cuvette. Record the color of the equilibrium mixture in the Model 1 Data Table— After reacting.

8. Select "Blue (468 nm) Absorb" for the colorimeter.

9. Place the cuvette into the colorimeter, close the top, and start data collection.

10. Once the reading stops fluctuating, record the absorbance in the Model 1 Data Table.

11. Clean up all solutions and equipment according to your instructor's instructions.

Model 1 – K_c as a Constant

Table 1: Model 1 Data Table—Before reacting

Parameter	Iron(III) nitrate	Potassium thiocyanate
Concentration	0.0080 M	0.0010 M
Volume	3.0 mL	3.0 mL
Color	Yellow	Clear

Table 2: Model 1 Data Table—After reacting

Parameter	Equilibrium Mixture
Color	Red
Absorbance	1.217

Analyzing Model 1 – K_c as a Constant

12. Consider the equilibrium system in Model 1. When the two solutions were mixed in the beaker, which of the following calculations represent the initial concentration of Fe^{3+} ions in the mixture? Circle your answer.

$3.00 \text{ mL} \times 0.0080 \text{ M} = 2.40 \times 10^{-5} \text{ M } Fe^{3+}$ OR $\dfrac{3.00 \text{ mL} \times 0.0080 \text{ M}}{6.0 \text{ mL (total volume of solution)}} = 0.0040 \text{ M } Fe^{3+}$

Students should circle the calculation on the right. This question addresses the misconception of dimensional analysis, where the meaning of the unit of *molarity* is often unclear.

13. What is the initial concentration of SCN^- ions in the mixture?

$\dfrac{3.00 \text{ mL} \times 0.0010 \text{ M}}{6.0 \text{ mL (total volume of solution)}} = 0.0005 \text{ M } SCN^-$

14. Complete the following ICE table and equilibrium expression for this equilibrium system using the volumes and concentrations of the reactants in Model 1.

Table 3: ICE table for calculating equilibrium concentrations

Condition	Fe^{3+}	$+ SCN^-$	$\rightleftharpoons$	$FeSCN^{2+}$
I (Initial concentration)	0.0040 M	0.0005 M		0.0000 M
C (Change)	− x	− x		+ x
E (Equilibrium concentration)	0.0040 – x	0.0005 – x		+ x

$K_c = \dfrac{[FeSCN^{2+}]}{[Fe^{3+}][SCN^-]}$

$K_c = \dfrac{x}{(0.0040 - x)(0.0005 - x)}$

15. If K_c is not known, describe how you could use a spectrophotometer or a colorimeter to find x or $[FeSCN^{2+}]_{eq}$ in the lab.

   NOTE: This procedure is in the Light, Color, and Concentration lab.

   Use Beer's Law: *A* = *abc*; *x* = c = (Absorbance from colorimeter/*ab*), where *ab* = molar absorptivity × path length. You can also use a linear graph of *A* versus *c* to find the concentration.

16. Determine the equilibrium constant. Assume (path length × molar absorptivity) for this system is 5900 M^{-1}.

$A = 1.217$

$$\frac{Absorbance}{5900 \text{ M}^{-1}} = [FeSCN^{2+}] = x$$

$$x = \frac{1.217}{5900 \text{ M}^{-1}} = 2.1 \times 10^{-4} \text{ M}$$

$$K_c = \frac{x}{(0.0040 - x)(0.0005 - x)} = \frac{2.1 \times 10^{-4}}{(0.0040 - 2.1 \times 10^{-4})(0.0005 - 2.1 \times 10^{-4})}$$

$K_c = 191.1$

17. How does the value of your equilibrium constant compare to the values of the other groups in your class?

Table 4: Compare class results

Group	Equilibrium Constant
1	191.1
2	
3	
4	
5	
6	
7	
8	
9	
10	

The answer will vary, depending on the class data.

18. Is your data similar to that of your classmates? What should you do if your sample deviates by a significant amount?

NOTE: Often the equilibrium constant is considered constant when it varies within a power of ten.

Ideally, data is similar. If not, the trial should be performed again with more scrutiny.

MODEL 2

Building Model 2 – Adding Stress to an Equilibrium System

1. Obtain a test tube, test tube rack and marking pen.

2. Label the test tube "K" and place it in the test tube rack.

3. Add approximately 0.5 g of cobalt chloride hexahydrate into the test tube. Then add 10 drops of distilled water using a pipet and mix the solution with a glass stirring rod. This solution will remain untouched during the lab and represents the original condition of the cobalt system:

$$Co(H_2O)_6^{2+}(aq) + 4Cl^-(aq) \rightleftharpoons 6H_2O(l) + CoCl_4^{2-}(aq)$$

   Pink   Blue
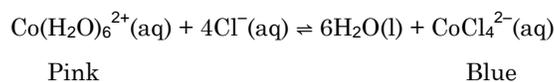
4. Repeat the previous step for two more test tubes and label them "A" and "B". Record your initial observations for all of the solutions in the Model 2 Data Table.

    NOTE: Hold the test tubes over a white background to make your observations easier.

❓ 5. HCl will be added to test tubes A and B. Will this addition increase or decrease the concentration of chloride ions in the equilibrium system? Explain.

    There will first be an increase because of the added chloride ion. As equilibrium is reached, the concentration of chloride ion will decrease as $CoCl_4^{2-}$ is formed. The concentration of $CoCl_4^{2-}$ will therefore increase.

6. While wearing gloves, carefully add 6.0 M HCl, drop-wise, to test tube A until a noticeable change has occurred. Then add the 6.0 M HCl, drop-wise, to test tube B. Record your observations in the Model 2 Data Table.

❓ 7. $AgNO_3$ will be added to test tube B and a precipitate should form. What reaction will occur to produce this precipitate? Write the net ionic reaction.

    The silver will react with the chloride ions to produce solid silver chloride.

    $Ag^+(aq) + Cl^-(aq) \rightleftharpoons AgCl(s)$
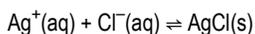
❓ 8. Should the formation of a precipitate increase or decrease the concentration of chloride ions in the equilibrium system? Explain.

    It should decrease the concentration of chloride ions. Chloride ions were removed to form the silver chloride solid and are no longer in solution.

9. While wearing gloves, add 0.1 M $AgNO_3$ drop-wise to test tube B until a color change is produced. You should notice a precipitate on the bottom of the test tube. Record your observations in the Model 2 Data Table.

    NOTE: Don't discard the solutions. You will use the solution in test tube A in Model 3.

Model 2 – Adding Stress to an Equilibrium System

Table 5: Model 2 Data Table—Results of adding stress

Test Tube	Color of the Solution		
	Initial Observations	After Addition of HCl	After Addition of AgNO$_3$
K	Pink		
A	Pink	Blue	
B	Pink	Blue	Pink

Analyzing Model 2 – Adding Stress to an Equilibrium System

10. In all test tubes, what color is the solution prior to the addition of the HCl or AgNO$_3$?

    The solution is pink.

11. Considering the appearance of the solution prior to the addition of HCl or AgNO$_3$, are there more products or reactants present at equilibrium? Explain your reasoning.

    There are more reactants. The solution is pink, the color of one of the reactants.

12. After adding HCl, what observation indicated that the reaction shifted to re-establish equilibrium?

    The color changed.

13. From the appearance of the solution in test tubes A and B after the addition of HCl, are there more products or reactants present at this re-established equilibrium position? Explain your reasoning.

    There are more products because the solution is blue, the color of one of the products.

14. Upon the addition of HCl, is the value of the reaction quotient Q greater than, less than or equal to value of K_c? Write the reaction quotient and use it to explain your answer.

$$Q = \frac{\left[CoCl_4^{-2}\right]}{\left[Co(H_2O)_6^{+2}\right]\left[Cl^-\right]^4}$$

    Since [Cl$^-$] increased, the value of $Q < K_c$.

15. Based on the observations in Model 2, does the reaction shift to the left, increasing the concentration of the reactants or to the right, increasing the concentration of products upon the addition of HCl?

    The solution turned blue, so it shifts to the right.

16. Have the concentrations of $Co(H_2O)_6^{2+}$ and $CoCl_4^{2-}$ increased or decreased after hydrochloric acid is added?

    As hydrochloric acid is added, the concentration of $CoCl_4^{2-}$ increases and the concentration of $Co(H_2O)_6^{2+}$ decreases.

17. The addition of silver nitrate to the equilibrium system created a change to the system by removing Cl$^-$ ions through a precipitation reaction. How does the new concentration of Cl$^-$ in test tube B compare to the Cl$^-$ concentration in test tube A?

    The concentration of Cl$^-$ in test tube B, after Ag$^+$ is added, is ___<___ the concentration of
    <, >, or =
    Cl$^-$ in test tube A.

18. Upon the addition of $AgNO_3$, is the value of the reaction quotient greater than, less than or equal to value of K_c? Write the reaction quotient and use it to explain your answer.

$$Q = \frac{\left[CoCl_4^{-2} \right]}{\left[Co(H_2O)_6^{+2} \right]\left[Cl^- \right]^4}$$

Since [Cl⁻] decreased, the value of $Q > K_c$.

19. Based on the observations in Model 2, does the reaction shift to the left (more reactants) or right (more products) upon the addition of $AgNO_3$?

The solution turned pink, indicating it shifted to the left.

20. Did the concentrations of $Co(H_2O)_6^{2+}$ and $CoCl_4^{2-}$ increase or decrease after silver nitrate was added?

After silver nitrate was added, the concentration of $CoCl_4^{2-}$ decreased and the concentration of $Co(H_2O)_6^{2+}$ increased.

21. Model 2 dealt with the following equilibrium system:

$$Co(H_2O)_6^{2+}(aq) + 4Cl^-(aq) \rightleftharpoons 6H_2O(l) + CoCl_4^{2-}(aq)$$

Pink   Blue
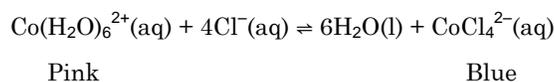
a. Complete the table to indicate how experimental stresses due to changing the amounts of substances in the solution shifted the equilibrium.

Table 6: Stress results due to changing reactant amounts

Stress	Resulting Color	Direction of Shift	Q vs K_c (<, >, =)
Removal of Cl^-	Pink	Left (toward reactants)	$Q \ \underline{\ <\ } \ K_c$
Addition of Cl^-	Blue	Right (toward products)	$Q \ \underline{\ >\ } \ K_c$

b. Predict how the following stresses in the amounts of substances would shift the equilibrium in the solution.

Table 7: Stress result predictions

Stresses That Could Cause This Shift	Resulting Color	Direction of Shift	Q vs K_c (<, >, =)
Removal of $Co(H_2O)_6^{2+}$	Pink	Left (toward reactants)	$Q \ \underline{\ <\ } \ K_c$
Addition of $Co(H_2O)_6^{2+}$	Blue	Right (toward products)	$Q \ \underline{\ >\ } \ K_c$
Removal of $CoCl_4^{2-}$	Blue	Right (toward products)	$Q \ \underline{\ >\ } \ K_c$
Addition of $CoCl_4^{2-}$	Pink	Left (toward reactants)	$Q \ \underline{\ <\ } \ K_c$

22. The solutions in test tube K, test tube A (after the addition of HCl) and test tube B (after the addition of AgNO₃) are all at equilibrium. Which of the following must be true about the solutions in the three test tubes? Circle the correct answer.

   i. They have the same amounts of reactants and products, same value of K_c, same color of equilibrium mixture.

   ii. They have different amounts of reactants and products, different values of K_c, different color of equilibrium mixture.

   iii. They have the same amounts of reactants and products, same value of K_c, different color of equilibrium mixture.

   iv. They have different amounts of reactants and products, same value of K_c, different color of equilibrium mixture.

   The answer is iv: Different amounts of reactants and products, same value of K_c, different color of equilibrium mixture.

MODEL 3

Building Model 3 – Endothermic or Exothermic

1. Connect a temperate sensor to your data collection system.

2. Set up a warm water bath using a hot plate and a 250-mL beaker, and a cold water bath using ice water and a 250-mL beaker.

❷ 3. What lab observation will confirm that the reaction studied in Model 2 is endothermic? Why?

   The reaction is endothermic if, in a hot water bath, the system turns blue. In an endothermic reaction, heat acts like a reactant and an increase in temperature will cause the reaction to shift right to reduce the stress.

❷ 4. What lab observation will confirm that the reaction is exothermic? Why?

   The reaction is exothermic if, in a hot water bath, the system turns pink. In an exothermic reaction, heat acts like a product and an increase in temperature will cause the reaction to shift left to reduce the stress.

5. Place test tube A into the hot water bath for three minutes and then into the cold water bath for three minutes. Record your observation for each situation in the Model 3 Data Table.

6. Clean up all solutions and equipment according to your instructor's instructions.

Model 3 – Endothermic or Exothermic

Table 8: Model 3 Data Table—Results of hot and cold stress

Condition	Resulting Color
After 3 minutes in hot water	Blue
After 3 minutes in ice water	Pink

Analyzing Model 3 – Endothermic or Exothermic

7. Is the cobalt equilibrium system endothermic or exothermic? Why? Provide evidence from your lab that supports your claim.

    The reaction is endothermic because the solution turned blue in a hot water bath. The heat caused the reaction to shift towards the products.

8. Add energy to the appropriate side of the equation below.

    Heat + $Co(H_2O)_6^{2+}(aq) + 4Cl^-(aq) \rightleftharpoons 6H_2O(l) + CoCl_4^{2-}(aq)$
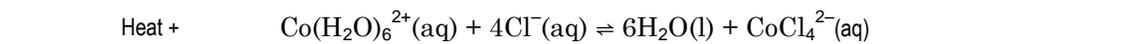
    Heat should be written on the reactants side for an endothermic reaction.

Connecting to Theory

Within five years of Henry Louis Le Châtelier abandoning his search for the synthesis of ammonia, Fritz Haber was able to create ammonia from hydrogen and nitrogen gas. The Haber process is used in industry to manufacture ammonia, a key component in fertilizer. Ammonia-based fertilizer is responsible for sustaining one-third of the earth's population, so this is a very important process. Ammonia is produced through the following catalyzed reaction:

$$N_2(g) + 3H_2 (g) \rightleftharpoons 2NH_3 (g) + heat$$
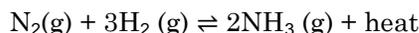
Under normal conditions, the yield of ammonia is only 10–20%. This is not enough to keep up with global demand of ammonia.

Le Châtelier's principle is often used to manipulate the outcomes of reversible reactions to maximize yield. If a system in dynamic equilibrium is subjected to a stress such as changes in concentration, temperature, volume, and partial pressures, the concentration of products and reactants change to reestablish the equilibrium constant, K_c . Quantitatively, the direction the reaction shifts to re-establish equilibrium can be determined by comparing the value of Q to the value of K_c.

Applying Your Knowledge – Determining a Constant Equilibrium Constant

1. With your group, design an experiment using the iron(III) thiocyanate equilibrium system to show that K_c remains constant when temperature is constant, within experimental error, despite different stresses added to the system. Record your procedure below.

    While designing your lab, keep the following items in mind:

    *   Change only one variable when creating a stress to the system.

    *   Calibrate the colorimeter prior to use.

    *   Excess SCN^- produces colored side products; keep SCN^- as the limiting reactant at 0.0010 M.

    *   Keep all iron solutions at low concentrations (0.0080 M or lower) so as to not overload the colorimeter.

    *   You may dilute solutions more using distilled water.

    *   Minimize fingerprints.

    *   If using a colorimeter, use blue, 468 nm, to measure absorbance.

    *   If using a colorimeter, assume (path length × molar absorptivity) for this system is 5900 M^{-1}.

- Create any data tables needed to organize data.

- Obtain your instructor's initials before you perform the lab.

Procedure:

Calibrate the colorimeter. the wavelength specified above (blue, 468 nm).

Use the following reaction:

$$Fe^{3+}(aq) + SCN^-(aq) \rightleftharpoons FeSCN^{2+}(aq)$$

Red
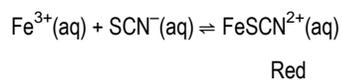
Use a 0.0010 M KSCN solution.

Make dilutions of the 0.0080 M iron nitrate.

The concentration of Fe^{2+} will be changed as the concentration of SCN^- is held constant. The Fe^{2+} concentrations are: 0.0040 M, 0.0025 M, 0.0020 M, 0.0010 M, and 0.0005 M.

After mixing 3 mL of each solution in a beaker, place the solution into a cuvette. Record the absorbance.

Repeat with the next two solutions until all Fe^{2+} concentrations have been tested.

Use similar calculations as in Model 1.

Instructor Initials: _____

Data Table(s):

Sample Data

Trial	Concentration Fe^{2+}	Concentration SCN^-	Absorbance	Concentration of FeSCN	K_c
1	0.0040	0.0005	1.217	2.1×10^{-4}	191.1
2	0.0025	0.0005	0.810	1.4×10^{-4}	160.2
3	0.0020	0.0005	0.547	9.3×10^{-5}	119.3
4	0.0010	0.0005	0.358	6.1×10^{-5}	148.0
5	0.0005	0.0005	0.182	3.1×10^{-5}	140.9

Calculations:

Sample calculations for Trial 1:

$A = abc$

$$\frac{A}{5900 \text{ M}^{-1}} = [\text{FeSCN}^{2+}]$$

$$\frac{1.217}{5900 \text{ M}^{-1}} = 2.1 \times 10^{-4} \text{ M}$$

$\text{Fe}^{3+}(aq) + \text{SCN}^{-}(aq) \rightleftharpoons \text{FeSCN}^{2+}(aq)$
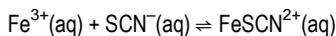
$$K_c = \frac{\left[\text{FeSCN}^{2+}\right]}{\left[\text{Fe}^{3+}\right]\left[\text{SCN}^{-}\right]}$$

Using the ICE table in Model 1:

$$K_c = \frac{x}{(0.0040 - x)\,(0.0005 - x)} = \frac{2.1 \times 10^{-4}}{(0.0040 - 2.1 \times 10^{-4})\,(0.0005 - 2.1 \times 10^{-4})}$$

2. Does K_c remain constant after stresses are added to the equilibrium? Why? Provide evidence from your lab that supports your claim.

   K_c ranges from 119.3 to 191.1. Often equilibrium is considered constant when it varies within a power of ten. In this case they are all with in a power of ten.

   Equilibrium constants are only changed when the reaction temperature changes. According to Le Châtelier, the system will reestablish the equilibrium (and constant) when concentration and pressure change. Thus, the system will reestablish equilibrium by rearranging the products and reactants until their quotient becomes equal to the equilibrium constant.

13. SHAPE OF TITRATION CURVES

Initial Question

A titration curve has a distinctive shape that often catches students by surprise. The shape of this curve changes predictably when weak acids are substituted for strong acids. Other parameters can also cause it to change. Once you have an understanding of the fundamental shape, a great deal of information can be derived from a titration curve.

What factors influence the shape of a titration curve?

Learning Objectives[*]

Students will manipulate the shape of titration curves.

LO 1.20 / The student can design, and/or interpret data from an experiment that uses titration to determine the concentration of an analyte in a solution.

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

LO 6.13 / The student can interpret titration data for monoprotic or polyprotic acids involving titration of a weak or strong acid by a strong base (or a weak or strong base by a strong acid) to determine the concentration of the titrant and the pK_a for a weak acid, or the pK_b for a weak base

SP 4.1 / The student can *justify the selection of the kind of data* needed to answer a particular scientific question.

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

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

Time Requirement

Preparation time: 30 minutes / Lab activity: 90 minutes

Materials and Equipment

Models 1, 2, and Applying Your Knowledge

- Data collection system
- pH sensor[1]
- Drop counter
- Drop dispenser[2]:
   Syringe, 60-mL, Stopcock (2), Drop tip
- Beaker, glass, 150-mL
- Beaker, 250-mL
- Mohr pipet, 25-mL
- Pipet pump

- Magnetic stirrer (stir plate)
- Micro stir bar
- Multi clamp
- Ring stand
- Three-finger clamp
- Distilled water
- Wash bottle
- Materials for drop counter and pH sensor calibration (refer to Appendix A)

[1]Included with PASCO Advanced Chemistry Sensor.
[2]Included with PASCO Drop Counter.

Model 1

- 0.10 M Sodium hydroxide (NaOH), 260 mL[1]
- 0.10 M Hydrochloric acid (HCl), 20 mL[1]
- Phenolphthalein indicator solution, 2 drops

[1]To formulate the chemical solutions, refer to the Lab Preparation section.

Model 2

- 0.10 M Sodium hydroxide (NaOH), 260 mL[1,2]
- 0.10 M Hydrochloric acid (HCl), 20 mL[1,2]
- 0.05 M Hydrochloric acid (HCl), 20 mL[1,2]
- 0.025 M Hydrochloric acid (HCl), 20 mL[1,2]
- 0.10 M Acetic acid (CH_3COOH), 20 mL[1,2]
- 0.10 M Potassium hydrogen tartrate ($KC_4H_5O_6$), 20 mL[1,2]

[1]To formulate the chemical solutions, refer to the Lab Preparation section.

[2]Not all solutions are needed by each group. Solutions used depend on the variable to be studied.

Applying Your Knowledge

- 0.10 M Sodium hydroxide (NaOH), 260 mL[1]
- Unknown acid of unknown concentration, 15 mL[1]

[1]To formulate the unknown acid, 0.2 M HCl, refer to the Lab Preparation section.

Prerequisites

Students should be familiar with the following concepts:

- K_a expressions
- Calculations involving pH, [H^+], molarity calculations
- Neutralization reactions
- Acids and bases, including strength and ionization.
- Basic understanding of the pH scale.
- Basic skills in performing a titration. Students should have performed either an indicator acid–base titration or a redox titration before attempting this lab.
- Acid–base titrations conducted with a pH probe
- Reaction stoichiometry

Lab Preparation

These are the materials and equipment to set up prior to the lab:

Model 1, Model 2, and Applying Your Knowledge

1. **0.10 M Sodium hydroxide:** To prepare 1000 mL of 0.10 M sodium hydroxide (NaOH), fill a 1000-mL volumetric flask 1/3 full of distilled water. Add 3.999 g of sodium hydroxide to the flask and swirl to dissolve. Fill to the line with distilled water.

Model 1 and Model 2

2. **0.10 M Hydrochloric acid:** To prepare 1000 mL of 0.10 M hydrochloric acid (HCl), fill a 1000-mL volumetric flask 1/3 full of distilled water. Add 8.27 mL of concentrated hydrochloric acid to the flask and swirl. Fill the flask to the line with distilled water.

Model 2

3. In this model, several titrations are to be carried out so that a graph is created for each of the four variables that affect the titration curve: a) number of moles; b) volume; c) concentration; d) K_a. Assign a variable to each student group so titrations for all variables are carried out. Students should share the data for the titrations they haven't done.

    Because concentration, volume, and number of moles are interrelated, refer to the answer at the end of Analyzing Model 1 for clarification of these variables for use in the titrations.

4. **0.05 M Hydrochloric acid:** To prepare 250 mL of 0.05 M hydrochloric acid, fill a 250-mL volumetric flask 1/3 full of distilled water. Add 125.0 mL of 0.10 M hydrochloric acid to the flask and swirl. Fill the flask to the line with distilled water.

5. **0.025 M Hydrochloric acid:** To prepare 250 mL of 0.025 M hydrochloric acid, fill a 250-mL volumetric flask 1/3 full of distilled water. Add 62.5 mL of 0.10 M hydrochloric acid to the flask and swirl. Fill the flask to the line with distilled water.

6. **0.10 M Acetic acid:** To prepare 250 mL of 0.10 M acetic acid (CH_3COOH), fill a 250-mL volumetric flask 1/3 full of distilled water. Add 1.44 mL of glacial acetic acid to the flask and swirl. Fill the flask to the line with distilled water.

7. **0.10 M Potassium hydrogen tartrate:** To prepare 250 mL of 0.10 M potassium hydrogen tartrate ($KC_4H_5O_6$), fill a 250-mL volumetric flask 1/3 full of distilled water. Add 4.704 g of potassium hydrogen tartrate to the flask and swirl. Fill the flask to the line with distilled water.

Applying Your Knowledge

8. **0.20 M Hydrochloric acid:** To prepare 1 L of 0.20 M hydrochloric acid, fill a 1-L volumetric flask 1/3 full of distilled water. Add 16.54 mL of concentrated hydrochloric acid to the flask and swirl. Fill the flask to the line with distilled water. Label this as "Unknown Acid, Unknown Concentration."

Safety

Add these important safety precautions to your normal laboratory procedures:

*   This lab uses strong acids and bases. In case of contact with your skin, wash off the solution with a large amount of water.

Getting Your Brain in Gear

1. Write a balanced chemical equation and net ionic equation for the reaction of a strong acid, HCl, with a strong base, NaOH.

   $HCl(aq) + NaOH(aq) \rightarrow H_2O + NaCl(aq)$

   $H^+(aq) + OH^-(aq) \rightleftharpoons H_2O$
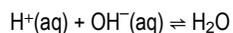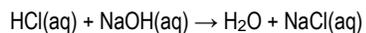
2. Write a balanced chemical equation and net ionic equation for the reaction of a weak acid, CH_3COOH with a strong base, NaOH.

   $CH_3COOH\ (aq) + NaOH(aq) \rightleftharpoons H_2O + CH_3COONa\ (aq)$

   $CH_3COOH\ (aq) + OH^-(aq) \rightleftharpoons H_2O + CH_3COO^-(aq)$
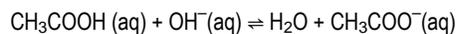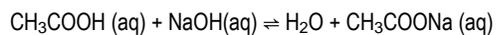
3. Calculate the volume of 0.25 M NaOH needed to completely react with 30.0 mL of 0.15 M HCl.

   Since there is a one-to-one ratio in the equation for NaOH and HCl, the same number of moles is needed for each solution:

   $(0.25\ M\ NaOH)(x) = (0.15\ M\ HCl)(30.0\ mL)$

   $x = 18.0\ mL$

MODEL 1

Building Model 1 – Titration of a Strong Acid with a Strong Base

1. Start a new experiment on the data collection system.

2. Use the multi-clamp to attach the drop counter to the ring stand. Use the illustration as a guide.

3. Use the three-finger clamp to attach the drop dispenser to the ring stand.

4. Rinse the drop dispenser syringe:

   a. Place a 250-mL beaker under the drop dispenser and open both stopcocks.

   b. Rinse the drop dispenser syringe and stopcock three times with approximately 20 mL of distilled water. This will remove any residue.

   c. Rinse the drop dispenser three times with 20 mL of the 0.10 M NaOH. This removes remaining water that would dilute the NaOH solution.

   d. Discard the rinse solution as directed by your teacher.

5. See Appendix A to set up and calibrate the drop counter and pH sensor.

   NOTE: Do not disconnect the drop counter from the data collection system or it will need to be calibrated again.

6. Assemble the rest of the apparatus using the following steps and the illustration as a guide.

   a. Position the magnetic stirrer on the base of the ring stand.

   b. Position the drop counter over the magnetic stirrer.

   c. Place the pH sensor through a large slot in the drop counter.

7. Display the pH on the *y*-axis of a graph and fluid volume on the *x*-axis.

8. Use the graduated pipet to transfer 20.00 mL of 0.10 M HCl and 30.0 mL of distilled water to a 150-mL beaker and set the beaker on the magnetic stirrer.
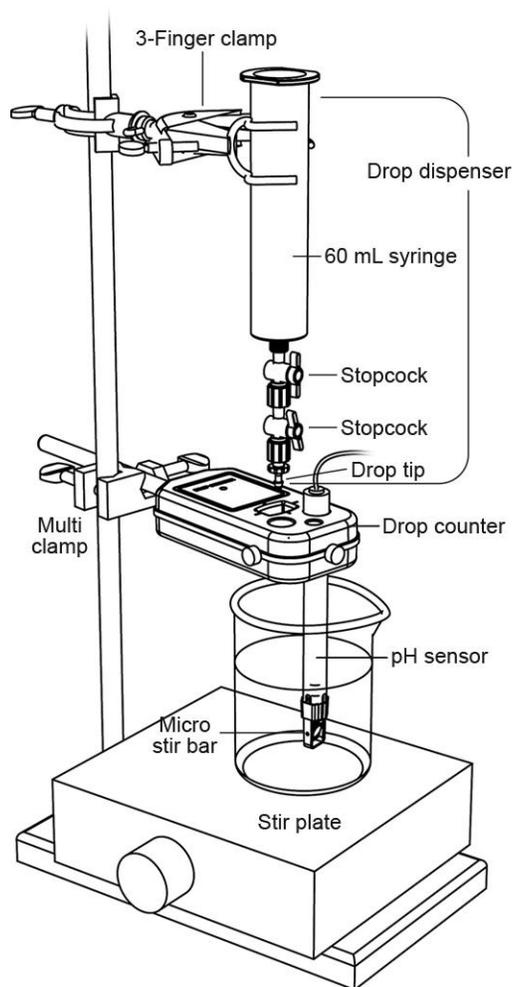
❷ 9. In this procedure you will be adding 0.10 M NaOH to the 0.10 M HCl analyte and measuring the pH as they mix. Predict what a graph of pH versus Volume of NaOH added will look like and sketch it below. Explain your reasoning.

Prediction
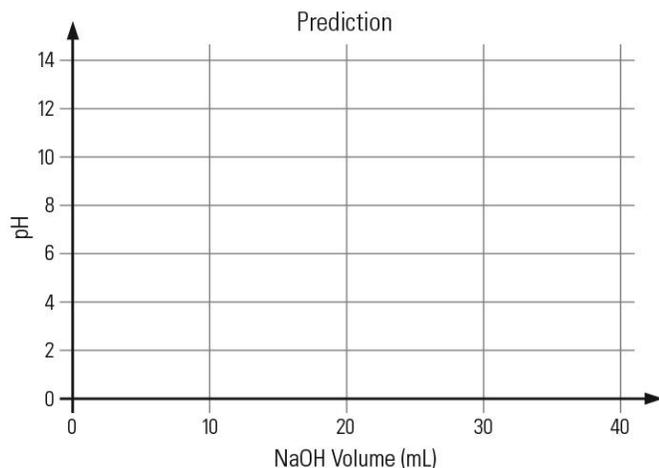
Answers will vary. Some students may sketch a linear relationship.

Twenty mL of the same concentration of HCl as NaOH was used, so the pH should change significantly the closer the volume of NaOH added comes to 20 mL.

10. Add two drops of phenolphthalein indicator solution to the solution in the beaker.

11. Turn on the magnetic stirrer at a slow and steady rate.

12. Start recording data.

13. Turn the drop dispenser stopcock carefully, allowing the titrant to drip slowly (1 to 2 drops per second) into the solution.

NOTE: The top valve controls the flow rate and the bottom valve turns the flow on and off.

14. Record in the Model 1 Data Table the approximate pH where the phenolphthalein turns from clear to pink and the volume of titrant used. Do not stop the titration at this point. Continue the titration until the pH curve flattens, somewhere between pH 10 and pH 14.

15. Stop recording data.

16. Save your experiment and dispose of the contents of the beaker according to your teacher's instructions.

17. Sketch or attach a copy of your graph of pH versus volume of NaOH added to Model 1. In the Model 1 Data Table, record the concentration of the base, the acid, and the volume of acid used.

Model 1 – Titration of a Strong Acid with a Strong Base

Table 1: Model 1 Data Table—Titration measurements

Titration Information	
Parameter	**Value**
Concentration of NaOH (M)	0.10 M
Concentration of HCl (M)	0.10 M
Volume of HCl sample (mL)	20.0 mL
Volume of titrant (NaOH) added when indictor changed color (mL)	20.0 mL
pH of indicator color change	7–8

pH vs Volume of NaOH
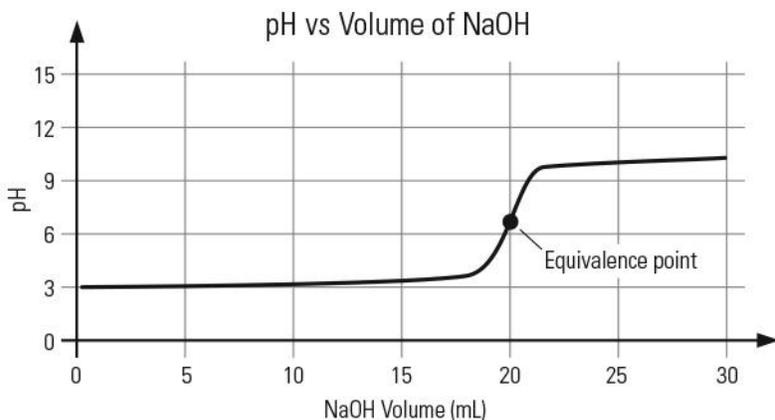
Analyzing Model 1 – Titration of a Strong Acid with a Strong Base

18. Compare your predicted titration graph with the one obtained in the lab. Reflect on any differences or similarities in the two graphs.

    Students often predict a linear relationship. The "S" shaped curve may be surprise for many students.

19. Assuming the reaction between HCl and NaOH goes to completion, because they are a strong acid and base, calculate the volume of 0.10 M NaOH needed to completely neutralize the acid in the beaker.

    Since there is a one-to-one ratio in the equation for NaOH and HCl, the same number of moles is needed for each solution:

    (0.10 M NaOH(x) = (0.10 M HCl)(20.0 mL)

    x = 20.0 mL NaOH

20. The point in the reaction at which the number of moles of base added equals the number of moles of acid originally present in the sample is called the *equivalence point*. What volume of 0.10 M NaOH needs to be added to your acid to reach the equivalence point?

    20 mL of 0.1 M NaOH is needed to reach the equivalence point.

21. Describe and label the equivalence point on the graph in Model 1.

    The equivalence point is the vertical section of the curve between pH 5 and 8.

22. For a strong acid–strong base titration, the pH at the equivalence point should be 7.

    a. Consider the products of the neutralization reaction and explain why an equivalence point pH of 7 makes sense.

    The pH of the equivalence point should be 7 because a strong acid–strong base neutralization results in all neutral products (water and a neutral salt).

    b. If the equivalence point pH of your graph is not close to 7, propose some sources of error that may have skewed your data.

    Inaccurate measurements of the acid are the most common cause of errors that skew data. Other errors include poor rinsing of glassware, poor rinsing of drop dispenser, and flow rates that are too fast for the sensor.

23. The endpoint of a titration occurs when the indicator solution changes colors. Compare the pH when the indicator changed color during your titration and the pH of the equivalence point on your graph. Describe any similarities.

    The pH values are similar.

24. The graph below was produced from the titration of a 20.0 mL sample of HCl of unknown concentration with 0.05 M NaOH. Calculate the concentration of HCl in the sample using data from the graph.

pH vs 0.05 M NaOH
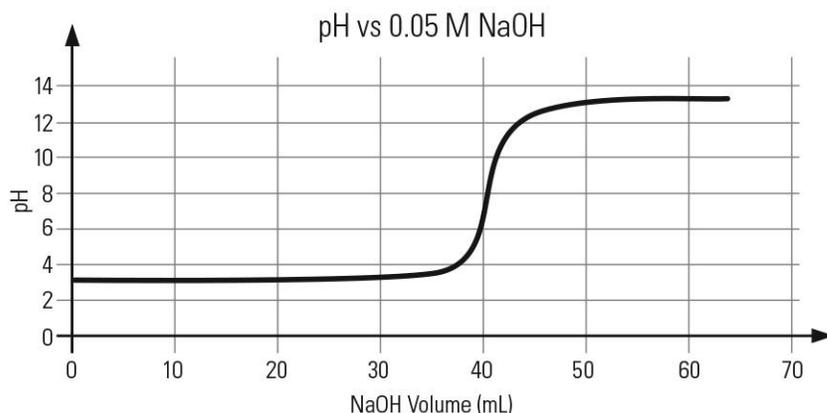
The equivalence point, where the pH is 7 occurs at 40.0 mL.

$V_1 M_1 = V_2 M_2$

20.0 mL × M_1 = 40.0 mL × 0.05 M NaOH

$M_1 = 0.10$ M HCl

25. There are several notable features of the shape of a titration curve besides the pH and volume coordinates of the equivalence point. These include the initial pH, the slope of the first section, and the slope at the end. Brainstorm some variables in a titration that might change one or more of these features in a titration curve. Share these ideas with your class.

Variables that change the shape of a titration curve, where the analyte is an acid and the titrant is a base, are: strength of the acid, acid concentration, volume of acid sample, and number of moles of analyte.

Because concentration, volume, and number of moles are interrelated, it can be confusing to determine what to change in order to apply the variables. The following definitions were used to obtain the graphs shown in Model 2:

- Acid strength varies: Use the same volume and concentration of the three different acids, HCl, CH_3COOH, and $KC_4H_5O_6$.

- Concentration varies: Use the same volume of different concentrations of HCl.

- Volume varies: Use the same volume and concentration of HCl, then add varying amounts of water.

- Number of moles varies: Use different volumes of the same acid concentration.

MODEL 2

Building Model 2 – Changing the Shape of a Titration Curve

Your instructor will assign you a variable from the class list generated in Model 1. Develop a procedure using the titration technique from Model 1 that will allow you to compare at least three titration curves produced while adjusting your assigned variable. Your titration curve in Model 1 can be one of the three curves you compare. Be prepared to present your findings to the class and explain how your variable affects the shape of a titration curve.

1. Before doing the next titration, use the Prediction Tool on the data collection system to draw what you think the graph will look like when you vary your assigned variable. Sketch or attach a copy of your graph.
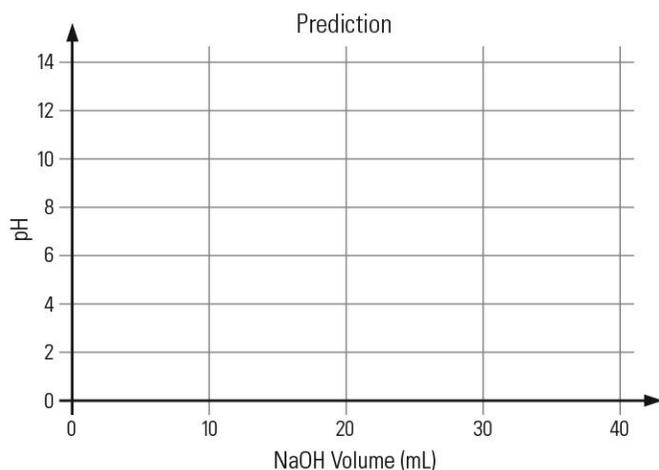
Answers will vary, depending on the variable the student has been assigned. Example graphs for each variable are in Model 2 below.

2. Carry out your procedure and complete the Model 2 Data Table.

Model 2 – Changing the Shape of a Titration Curve

Variable to be studied : Concentration

Table 2: Model 2 Data Table—Effect of changing the variable on the titration curve

	Trial 1 (from Model 1)	Trial 2	Trial 3
Concentration of NaOH used (M)	0.10	0.05	
Formula of acid used	HCl	HCl	
Titration Measurements			
Concentration of analyte (M)	0.10	0.10	
Volume of analyte (mL)	20.00	10.00	
Volume of titrant (mL)	10.0	10.0	
Number of moles of analyte (mol)	2.0×10^{-3}	1.0×10^{-3}	
Initial pH	2.80	2.81	

3. Graph—Sketch your graph here showing all three titration curves and record the value of the variable you changed.

Changed variable value:

Changed variable value:

Changed variable value:
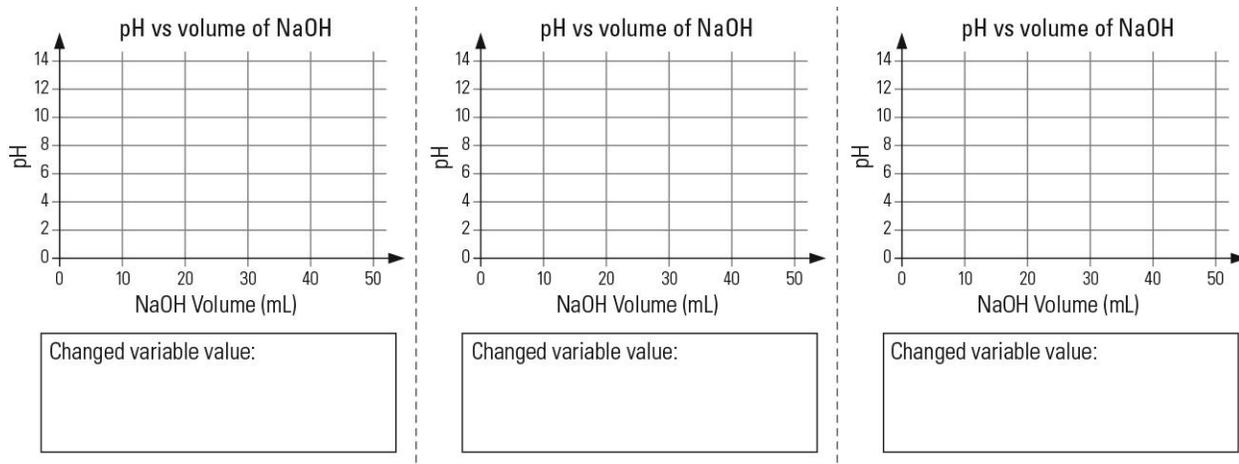
4. Class Data—Sketch the results of other groups who investigated the other titration variables, showing the three curves on a single graph. Label the four graphs as Graphs A–D and indicate the variable for each.

a) Variable: Number of moles

b) Variable: Volume

c) Variable: Concentration

d) Variable: Strength of acid
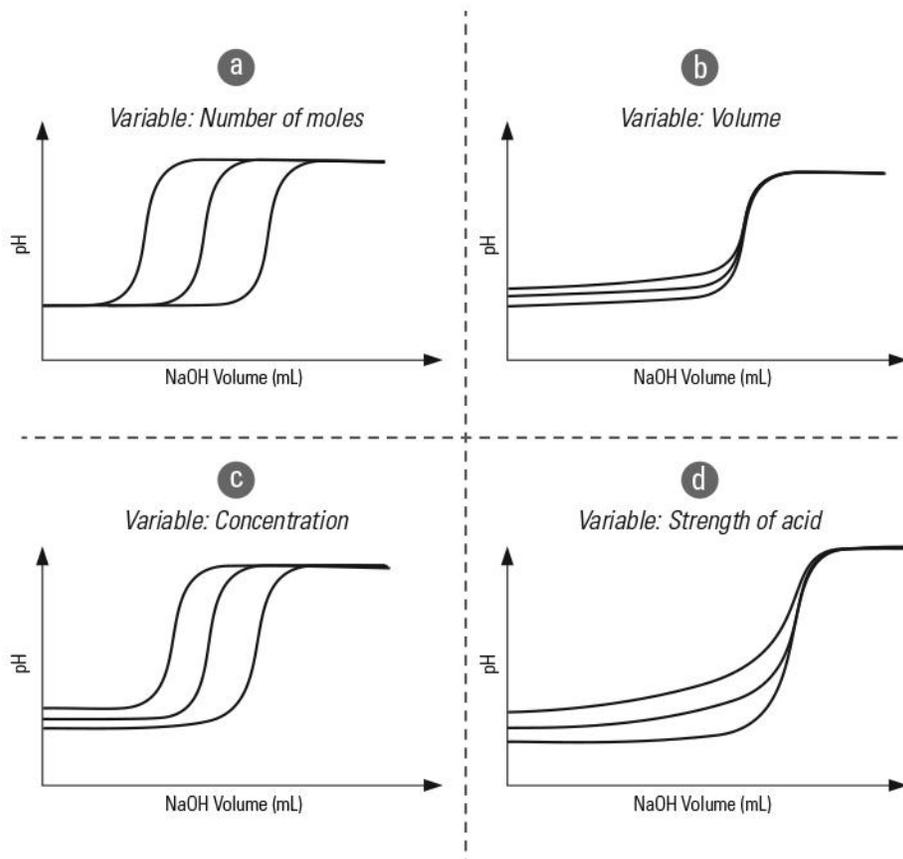
Analyzing Model 2 – Changing the Shape of a Titration Curve

5. There are four points on a titration curve that define the curve: the starting pH, the slope of the curve between the start and the equivalence point, the volume of titrant needed to reach the equivalence point, and the pH at the equivalence point.

    a. Which graph from the class data shows the effect of varying the number of moles of acid in the analyte (concentration is constant, analyte volume changes) on the titration curve?

    From the sample graphs, graph A.

    b. What feature(s) of the titration curve is(are) most affected by the number of moles of acid?

    The volume of titrant needed to reach the equivalence point.

6. a. Which graph from the class data shows the effect on the titration curve of differing volumes of sample (the number of moles of acid is constant, the concentration changes)?

    From the sample graphs, Graph B.

    b. What feature(s) of the titration curve is(are) most affected by the volume of the sample (using the same volume of analyte and varying the total volume by adding water)?

    The starting pH is affected.

7. a. Which graph from the class data shows the effect on the titration curve of differing concentrations of acid (volume is constant, the number of moles of acid changes).

    From the sample graphs, Graph C.

    b. What feature(s) of the titration curve is(are) most affected by the concentration of the sample?

    The initial pH and the volume of titrant needed to reach the equivalence point.

8. a. Which graph from the class data shows the effect on the titration curve of differing acid strength (acid concentration is constant, volume is constant)?

    From the sample graphs, Graph D.

    b. What feature(s) of the titration curve is(are) most affected by the strength of the acid sample (analyte)?

    The starting pH, the slope of the curve between the start and the equivalence point, and the pH at the equivalence point are all affected by the strength of the acid.

9. Refer to the following titration curves:
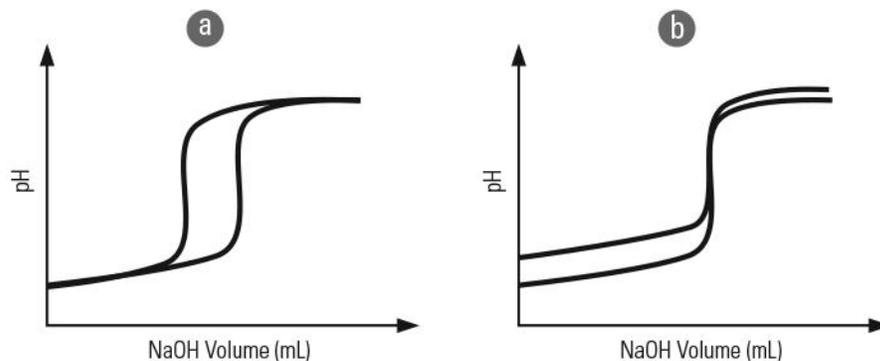
a. Which of the titration curves shows two titrations done with the same titrant and sample concentrations, but with acids of two different strengths?

The graph on the right shows acids of different strength.

b. In the graph that you chose above, which titration curve is from the weaker acid sample?

The acid that starts at a higher pH is the weaker acid.

Connecting to Theory

Titration is one of the most important analytical techniques in chemistry. It is one of the ways a scientist can determine how much of a substance is present in a sample. In this lab series, several types of titrations are encountered.

Titration can be performed using precipitation, the formation of complex molecules, and redox reactions. In an earlier lab you explored a thermometric titration which has a distinctive "V" shaped curve. Most titrations, including redox and acid–base titrations, have an "S" shape.

All titrations use a substance with a known concentration to determine the concentration of an unknown. In the next section, you are asked to use 0.10 M NaOH as the titrant to determine the concentration of an unknown acid.
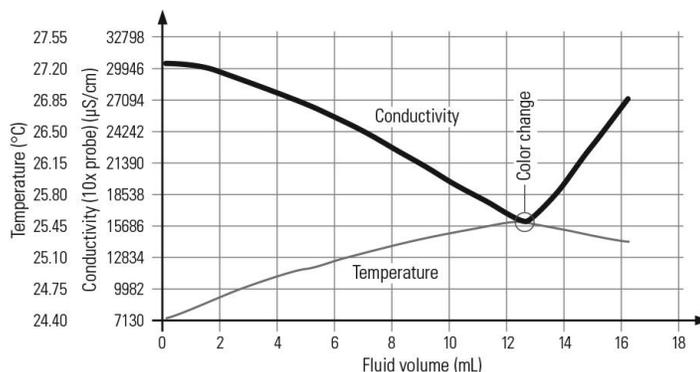
Applying Your Knowledge – Determining the Concentration of an Unknown Acid

You will be given 15 mL of an unknown monoprotic acid. Use 0.10 M NaOH and the titration equipment to determine the concentration of the unknown acid. Identify the equivalence point by making a graph of pH vs volume of base.

1. Create a data table. Record your titration measurements. Sketch or attach a copy of your graph of pH versus volume of NaOH.

    Applying Your Knowledge Data Table—Using titration to determine concentration

Titration Information	
Parameter	Value
Concentration of NaOH (M) (titrant)	0.10 M
Volume of acid sample (mL) (analyte)	15.0 mL
Volume of titrant at equivalence point (mL)	25.2 mL
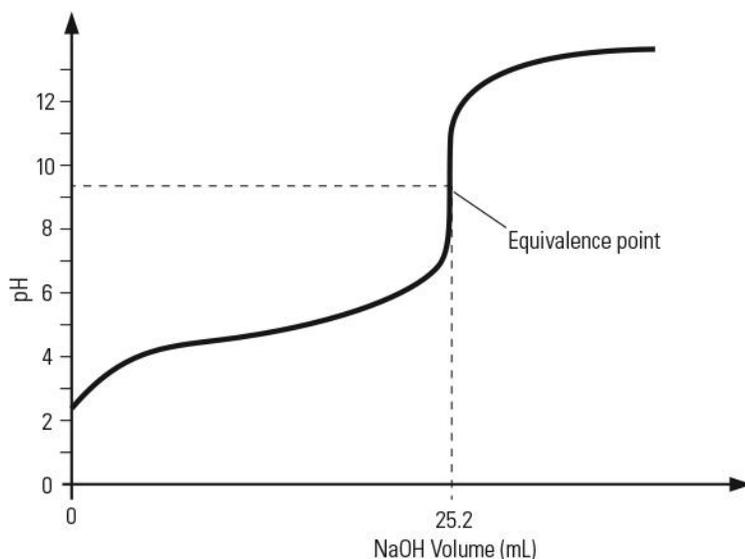
2. Which area of the graph is most critical in determining the concentration of the unknown acid? Why?

    The equivalence point is most critical because at that point all of the acid molecules are neutralized by the base and stoichiometry can be used.

3. Find the concentration of the unknown monoprotic acid.

    (0.10 M NaOH)(25.2 mL = M_2(15.0 mL)

    M_2= 0.17 M

4. Gather results from your peers. Compare your results and determine if your results are outside of a standard deviation.

    $$\text{Standard deviation} = \sqrt{\frac{\sum(x - \bar{x})^2}{n}}$$;

    $\bar{x}$ is the mean; n is the number of values

5. What action should you take if your data is outside of the standard deviation?

    Do the procedure again and pay more attention to details. For example, measure and record volumes accurately, set the magnetic stirrer at a slow and steady rate, and allow the titrant to drip slowly (1 to 2 drops per second) into the solution.

6.   What is the average molarity of the unknown acid?

Answers will vary, but they should be close to 0.20 M.

Teacher Tips

Tip 1 – Brainstorming variables

At the end of Model 1, students are asked to brainstorm variables in a titration that might change one or more of the features of a titration curve. You may need to guide the students to ensure that they have covered all of the variables in a titration with an acid analyte: strength of the acid, acid concentration, volume of acid sample, and number of moles of analyte.

Tip 2 – Variables

This lab will stretch students' comfort level with designing an experiment and defining variables. One of the variables, concentration, is the combination of two other variables: the volume and the number of moles of analyte. This provides a great opportunity to address the types of variables in an experiment.

There are four variables in a titration with an acid analyte: strength of the acid, acid concentration, volume of acid sample, and number of moles of analyte. Ideally, only one would change and the other three would be maintained as constant for each group of titrations. However, concentration, volume, and number of moles are interrelated, so two variables may need to be changed to control the third. Refer to the answer at the end of Analyzing Model 1 for details on handling the variables.

14. WEAK ACID TITRATION

Initial Question

Weak acids have a slightly different chemistry than strong acids. If the pH of a strong acid solution and a weak acid solution of equal concentration were analyzed, the weaker acid would have a higher pH. This is due to the partial ionization of the weak acid. However, if the weak acid is neutralized by a strong base, the weak acid is forced to ionize completely.

What information can you derive from a pH titration curve of a weak acid?

Learning Objectives[*]

Students titrate monoprotic and polyprotic weak acids and determine the relationship between the shapes of the curves and K_a.

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

LO 6.13 / The student can interpret titration data for monoprotic or polyprotic acids involving titration of a weak or strong acid by a strong base (or a weak or strong base by a strong acid) to determine the concentration of the titrant and the pK_a for a weak acid, or the pK_b for a weak base.

SP 1.4 / The student can *use representations and models* to analyze situations or solve problems qualitatively and quantitatively.

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

Time Requirement

Preparation time: 20 minutes / Lab activity: 90 minutes

Materials and Equipment

Model1, Model 2, and Applying Your Knowledge

- Data collection system
- pH sensor[1]
- Drop counter
- Drop dispenser[2]:
  Syringe, 60-mL / Stopcock (2) / Drop tip
- Beaker, glass, 150-mL
- Beaker, 250-mL
- Mohr pipet, 25-mL
- Magnetic stirrer (stir plate)

- Micro stir bar
- Pipet pump
- Multi clamp
- Ring stand
- Three-finger clamp
- 0.50 M Sodium hydroxide (NaOH), 160 mL[3]
- Distilled water, 260 mL
- Wash bottle
- Materials for drop counter and pH sensor calibration (refer to Appendix A)

[1]Included with PASCO Advanced Chemistry Sensor.
[2]Included with PASCO Drop Counter.
[3]To formulate the 0.50 M sodium hydroxide, refer to the Lab Preparation section.

[*] From AP Chemistry Course and Exam Description, Effective Fall 2013 (revised edition). Copyright (c) 2013 The College Board. Reproduced with permission. http://apcentral.collegeboard.com.

Model 1

• 1.0 M Acetic acid (CH_3COOH), 20 mL[1]

[1]To formulate the 1.0 M acetic acid, refer to the Lab Preparation section.

Model 2

• 0.05 M Maleic Acid ($C_3H_4O_4$), 50mL[1]

[1]To formulate the 0.05 M maleic acid, refer to the Lab Preparation section.

Applying Your Knowledge

• Aspirin tablet   • Mortar and Pestle

Prerequisites

Students should be familiar with the following concepts:

• Acids and bases, including strength, ionization, and conjugates.

• Basic understanding of the pH scale.

• Basic skills in performing a titration. Students should have performed either an indicator acid–base titration or a redox titration before attempting this lab.

• K_a and pK_a equations

Lab Preparation

These are the materials and equipment to set up prior to the lab:

All Models

1. **0.50 M Sodium hydroxide**: To prepare 1 L of 0.50 M sodium hydroxide (NaOH), fill a 1-L volumetric flask 1/3 full of distilled water. Add 20.000 g of sodium hydroxide to the flask and swirl to dissolve. Fill the flask to the line with distilled water.

Model 1

2. **1.0 M Acetic acid**: To prepare 1 L of 1.0 M acetic acid (CH_3COOH), place about 250 mL of distilled water into a 1-L volumetric flask. Add 57.47 mL of glacial acetic acid and then fill the flask to the line with distilled water.

Model 2

3. **0.05 M Maleic Acid**: To prepare 1 L of 0.05 M maleic acid ($C_3H_4O_4$), place about 250 mL of distilled water into a 1-L volumetric flask. Add 5.203 g of maleic acid and then fill the flask to the line with distilled water.

Safety

Add these important safety precautions to your normal laboratory procedures:

• Sodium hydroxide is caustic and should be handled with special care. In case of contact with your skin, wash off the sodium hydroxide with a large amount of water.

Getting Your Brain in Gear

1. Compare the ionization of a strong acid to that of a weak acid.

   Strong acids ionize 100%. Weak acids do not ionize completely.

2. Acetic acid is a weak monoprotic acid. Circle the ionizable hydrogen on the formula below.
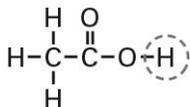
3. Analyze the following particulate-level representations of two acidic solutions. Label one beaker as the strong acid and the other as a weak acid. Explain your reasoning.
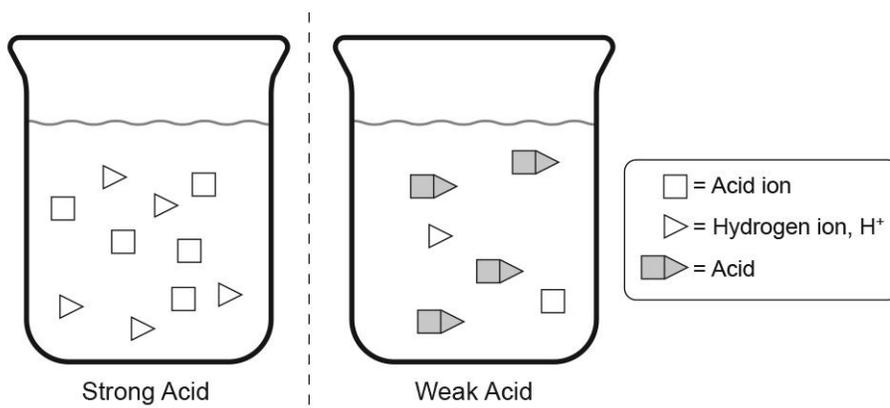
   The strong acid has ionized 100%. The weak acid is not ionized completely.

4. Write the K_a expression for the equation: $HA + H_2O \rightleftharpoons H_3O^+ + A^-$

   $$K_a = \frac{\left[H_3O^+\right]\left[A^-\right]}{\left[HA\right]}$$

5. Will the K_a of a weak acid be greater or less that the K_a of a strong acid? Why?

   The K_a will be less, because a weak acid does not dissociate completely, making the numerator, and therefore K_a, less than the K_a of a strong acid of the same concentration.

MODEL 1

Building Model 1 – pH Titration of a Weak Acid

1. Start a new experiment on the data collection system.

❷ 2. If 0.50 M sodium hydroxide solution is the titrant and the weak acid, HA, is the analyte, which solution should go into the buret (or syringe) and which should go into the beaker?

   The sodium hydroxide should go into the buret (or syringe) and the acid should go into the beaker.

3. Use the multi-clamp to attach the drop counter to the ring stand. Use the illustration as a guide.

4. Use the three-finger clamp to attach the drop dispenser to the ring stand.

5. Rinse the drop dispenser syringe:

   a. Place a 250-mL beaker under the drop dispenser and open both stopcocks.

   b. Rinse the drop dispenser syringe and stopcock three times with approximately 20 mL of distilled water. This will remove any residue.

   c. Rinse the drop dispenser three times with 20 mL of the 0.5 M NaOH. This removes remaining water that would dilute the NaOH solution.

   d. Discard the rinse solution as directed by your teacher.
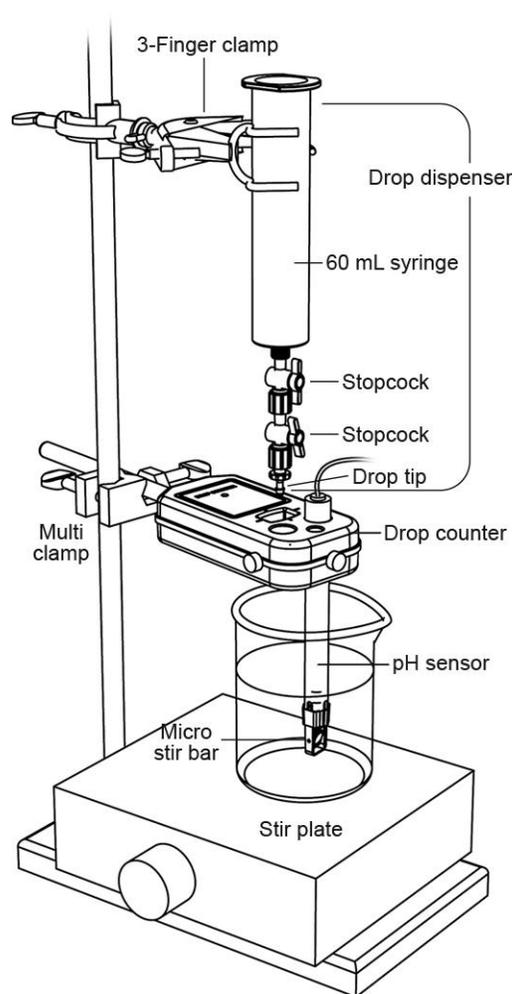
6. See Appendix A to set up and calibrate the drop counter and pH sensor and then set up the remaining equipment as illustrated.

   NOTE: Do not disconnect the drop counter from the data collection system or it will need to be calibrated again.

7. Display the pH on the *y*-axis of a graph and fluid volume on the *x*-axis.

8. Use the graduated pipet to transfer 10.00 mL of 1.00 M acetic acid solution to a 150-mL beaker and set the beaker on the magnetic stirrer as in the picture. Rinse the pipet with distilled water.

9. Add distilled water to the acid in the 150-mL beaker until the glass tip of the pH electrode is submerged.

❷ 10. In order for the tip of the pH electrode to be covered, distilled water must be added to the solution in the beaker.

   a. Does adding water to the analyte change the molarity of the sample?

Yes, the molarity will decrease.

b. Does adding water to the analyte change the number of moles of acid in the sample?

No, the same number of moles of solute is in the beaker.

c. Will adding water to the analyte affect the volume of titrant needed to reach the equivalence point for the titration? Explain your answer.

Additional water will change the molarity but not the number of moles of acid. In titration, the number of moles of base is balanced with the number of moles of acid, so the volume of titrant needed is not affected.

11. Turn on the magnetic stirrer at a slow and steady rate.

12. Start recording data.

13. Turn the drop dispenser stopcock carefully, allowing the titrant to drip slowly at a rate of 1 to 2 drops per second into the solution.

   NOTE: The top valve controls the flow rate and the bottom valve turns the flow on and off.

14. Continue the titration until the pH curve flattens, at around pH 12–14.

15. Stop recording data.

16. Save your experiment and dispose of the contents of the beaker according to your teacher's instructions.

17. Sketch or attach a copy of your graph of pH versus volume of NaOH added to Model 1. In the Model 1 Data Table, record the concentration of the base and the weak acid, and the volume of the weak acid used.

Model 1 – pH Titration of a Weak Acid

Table 1: Model 1 Data Table—Determining the equivalence point

Titration Information	
Parameter	**Value**
Concentration of NaOH used (M)	0.50
Concentration of CH_3COOH used (M)	1.00
Volume of weak acid sample (mL)	10.00

Model 1 Graph
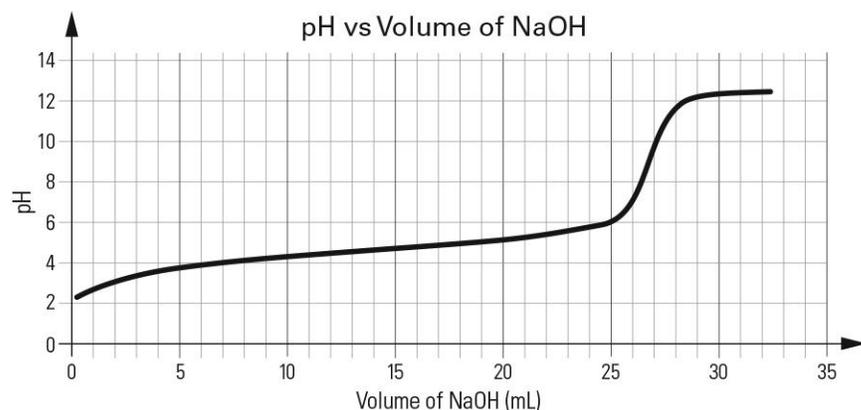
Analyzing Model 1 – pH Titration of a Weak Acid

18. Write the net ionic equation for the neutralization being performed in the titration.

    $CH_3COOH + OH^- \rightleftharpoons H_2O + CH_3COO^-$
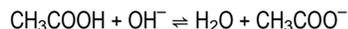
19. Answer the questions below to understand what information can be gained from a pH titration curve as the sodium hydroxide is added.

    a. Explain why the pH of the solution starts below 7.

    In the beginning, the beaker contained only acid and water.

    b. What is happening to the pH of the weak acid solution as sodium hydroxide is added to the beaker? Explain what process is changing the pH.

    The pH increases slowly, then rises quickly, and then increases again slowly and levels off.

    As the hydroxide ion is added to the acetic acid, it combines with hydrogen ions to form water. Water does not alter the pH so the pH rises slowly toward neutral as the hydrogen ion concentration decreases. Once all of the hydrogen ions from the acetic acid have combined with the hydroxide ion, additional base causes the pH to rise rapidly past neutral until it reaches the pH of the base.

    c. The *equivalence point* represents the point in the titration where a *stoichiometrically equivalent* amount of base has been added to the acid. Using your graph, at what volume of titrant does this occur?

    For the sample data, the equivalence point occurs at 27 mL, approximately the midpoint of the sharp increase.

    d. Describe the change in pH at or around the equivalence point.

    The pH increases rapidly at the equivalence point.

    e. Is the solution acidic, basic, or neutral at the equivalence point?

    The solution is basic.

    f. Using the net ionic equation for the reaction, identify the species present in the beaker at the equivalence point. Which species in the solution is responsible for the pH? Write a chemical reaction for that species reacting with water to support your answer.

    The species present are H_2O and CH_3COO^-

    CH_3COO^- is responsible for the pH.

    The CH_3COO^- reacts with water: $CH_3COO^- + H_2O \rightleftharpoons CH_3COOH + OH^-$

20. The half-equivalence point is the volume of titrant halfway between the start of the titration and the equivalence point. Answer the questions below to determine the half-equivalence point on your titration curve and the information it provides.

    a. Determine the volume of titrant at the half-equivalence point.

    For the sample data, since the equivalence point is at 27 mL, the half-equivalence point is at 13.5 mL.

    b. According to the titration curve, what is the pH at the half-equivalence point?

    pH = 4.45

    c. Calculate the concentration of hydronium ion, $[H_3O^+]$, at the half-equivalence point.

    $pH = -\log[H_3O^+]$

    $4.45 = -\log[H_3O^+]$

    $[H_3O^+] = 10^{-4.45} = 3.54 \times 10^{-5}$ M

d. Calculate the number of moles of weak acid HA present before the titration and the number of moles that remain at the half-equivalence point.

Initial number of moles of HA: 10.0 mL of 1.0 M solution = 0.010 L × 1 mol/L = 0.010 mol

Number of moles of HA at the half-equivalence point = (Initial number of moles of HA) /2 = 0.005 moles

e. Based on the balanced equation $CH_3COOH + OH^- \rightleftharpoons H_2O + CH_3COO^-$, calculate the number of moles of conjugate base A^- that have formed at the half-equivalence point.

Number of moles of HA $_{reacted}$ = Number of moles of A^- = 0.005 moles

f. How do the number of moles of HA and the number of moles of A^- compare at the half-equivalence point? Since the HA and A^- are in the same solution, how do the concentrations of HA and A^- compare at half equivalence point?

The number of moles is the same, so the concentration of each is the same at the half-equivalence point.

g. Write the acid ionization expression for a weak acid, HA.
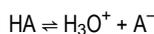
$HA \rightleftharpoons H_3O^+ + A^-$

$$K_a = \frac{[H_3O^+][A^-]}{[HA]}$$

h. Based on the relationship between the [HA] and [A^-] values, how can the acid ionization constant be simplified at the half-equivalence point?

$$K_a = \frac{[H_3O^+][A^-]}{[HA]} = \frac{[H_3O^+]\cancel{[A^-]}}{\cancel{[HA]}} = [H_3O^+]$$

i. How do the pK_a of the acid and the pH of the half-equivalence point compare?

pK_a = pH

They have the same value.

j. Explain why the half-equivalence point is the most useful point on the titration curve for determining the K_a of an unknown acid.

It is convenient to cancel out values that are mathematically equal in the K_a expression, so that the K_a can be obtained by knowing the pH at that point.

21. Label the pH titration graph below with the letters corresponding to the following items:

pH vs Volume of NaOH
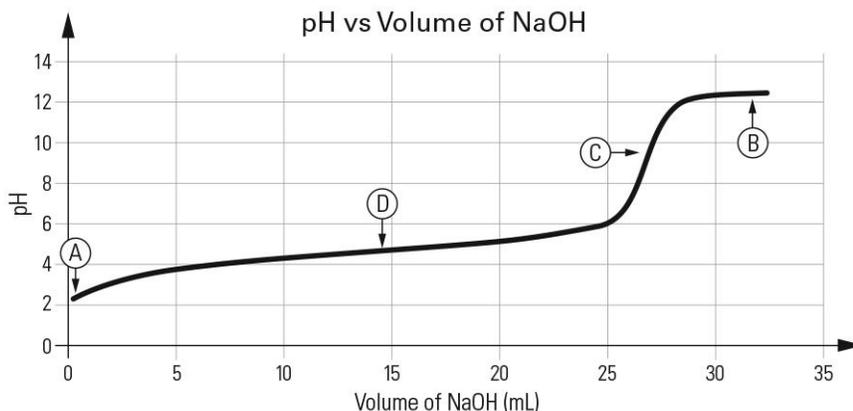
a. The point in the titration where the pH is determined by the concentration and strength of the weak acid sample.

b. The point in the titration where the pH is determined by excess titrant.

c. The point in the titration where the pH is determined by the concentration and strength of the conjugate base of the weak acid.

d. The point in the titration where the pH is equal to the pK_a.

22. Label the particulate view pictures below with the letters corresponding to the following items:

a. Before the titration

c. At the equivalence point

b. Halfway to the equivalence point

d. After the equivalence point
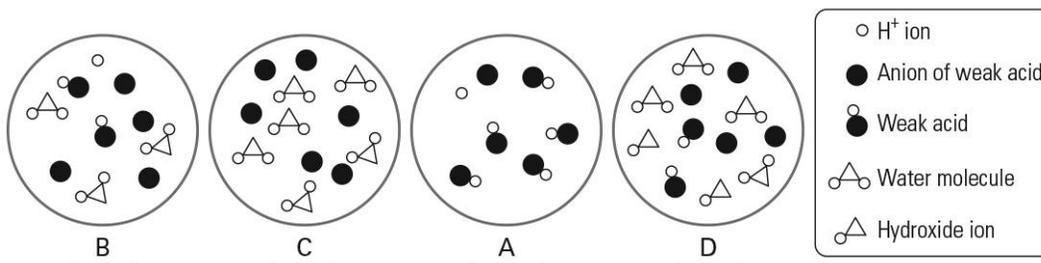
23. An alternate way of doing the titration in Model 1 would be to use an acid–base indicator to determine the equivalence point. Ideally, the end point of the titration, the point at which an added indicator changes color, should occur at or near the equivalence point of the titration—the point where the acid has completely reacted with the base.

a. Using the pH titration curve that you created in Model 1, at what volume would each indicator below begin to change colors?

Table 2: Using indicators to detect the equivalence point

Indicator	Color Change	pH Where Change Occurs	Volume When Change Begins
Methyl red	Red to Yellow	4.2 to 6.3	12.0 mL[1]
Bromothymol blue	Yellow to Blue	6.0 to 7.6	26.0 mL[1]
Phenolphthalein	Clear to Pink	8.0 to 9.6	26.5 mL[1]

[1]These vales apply to the sample data.

b. Which indicator in the table above would have best identified the equivalence point of the titration in Model 1?

Phenolphthalein

MODEL 2

Building Model 2 – pH Titration of a Weak Polyprotic Acid

NOTE: If the drop counter has been disconnected from the data collection system, it will need to be calibrated (see Appendix A).

1. Set up the titration as you did in Model 1. Use the graduated pipet to transfer 50.00 mL of 0.05 M maleic acid solution to a 150-mL beaker and set the beaker on the magnetic stirrer.

2. Add distilled water to the acid in the 150-mL beaker until the glass tip of the pH electrode is submerged.

3. Turn on the magnetic stirrer at a slow and steady rate.

4. Start recording data.

5. Turn the drop dispenser stopcock carefully, allowing the titrant to drip slowly at a rate of 1 to 2 drops per second into the solution.

6. Continue the titration until the pH curve flattens, at around pH 12–14.

7. Stop recording data.

8. Save your experiment and dispose of the contents of the beaker according to your teacher's instructions.

9. Sketch or attach a copy of your Model 2 graph of pH versus volume of NaOH added. In the Model 2 Data Table, record the concentration of the base and the weak acid, and the volume of the weak acid used.

Model 2 – pH Titration of a Weak Polyprotic Acid

Model 2 Graph
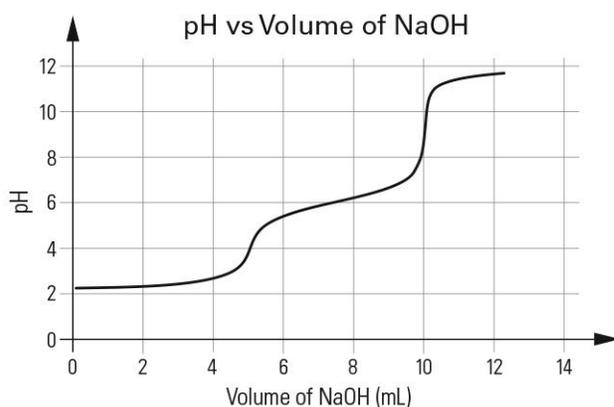
Table 3: Model 2 Data Table—Determining the equivalence point

Titration Information	
Parameter	**Value**
Concentration of NaOH used (M)	0.50
Concentration of $C_3H_4O_4$ used (M)	0.05
Volume of weak acid sample (mL)	50.0

Analyzing Model 2 – pH Titration of a Weak Polyprotic Acid

10. Below is the structural formula for maleic acid. Circle the hydrogen atoms that can ionize.
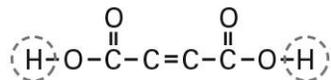
11. What features are different on the Model 2 graph as compared to the graph in Model 1?

    There are two sharp jumps in the pH, therefore there are two equivalence points.

12. How is the structure of maleic acid related to the titration curve?

    There are two ionizable hydrogens and two equivalence points in the titration curve.

13. Write the equation for the reaction of each hydrogen atom of maleic acid that ionizes with sodium hydroxide.

    $H_2C_4H_2O_4 + OH^- \rightleftharpoons HC_4H_2O_4^- + H_2O$

    $HC_4H_2O_4^- + OH^- \rightleftharpoons C_4H_2O_4^{2-} + H_2O$
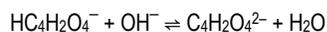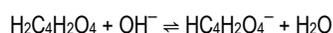
14. What volume of NaOH is required to reach each of the equivalence points?

    In the sample data, 5 mL of NaOH is required to reach the first equivalence point and 10 mL of NaOH is required to reach the second equivalence point.

15. Calculate the volume of titrant added to reach the half-equivalence point of each equivalence points.

    For equivalence point 1: (0 + 5 mL)/2 = 2.5 mL

    For equivalence point 2: (5 mL + 10 mL)/2 = 7.5 mL

16. Use the graph to determine the pH and pK_a at the half-equivalence points.

    At 2.5 mL, the pH = 2.21 so the pK_a = 2.21

    At 7.5 mL, the pH = 5.96 so the pK_a = 5.96

17. Record the literature values of the pK_a for maleic acid.

    pK_{a1} = 1.90

    pK_{a2} = 6.07

18. What is the percentage of error between the literature values and the values you determined from the titration?

    $\text{Percent error} = \left| \dfrac{1.90 - 2.21}{1.90} \right| \times 100 = 16.3\%$

    $\text{Percent error} = \left| \dfrac{6.07 - 5.96}{6.07} \right| \times 100 = 1.81\%$

Connecting to Theory

K_a is the symbol for the equilibrium constant for the ionization of an acid. The following equation describes the ionization of an acid:

$$HA + H_2O \rightleftharpoons H_3O^+ + A^-$$
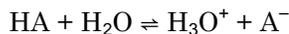
When equilibrium exists, the acid dissociation constant can be written as:

$$K_a = \frac{[H_3O^+][A^-]}{[HA]}$$

The value of K_a is an indication of the extent to which an acid dissociates. Strong acids dissociate nearly completely. Weak acids reach equilibrium, where the fraction that has dissociated remains constant at a given temperature. The numerical value of the equilibrium constant is unique to the acid and can be used to identify an unknown acid.

The half equivalence point is a very useful point in determining the K_a of an acid. At this point, the $[HA] = [A^-]$ so $K_a = [H_3O^+]$. Taking the negative log of both sides, the pK_a equals the pH.

Multiprotic acids are acids that have more than one acidic proton. Among organic molecules, those considered to be multiprotic have more than one carboxylic group (COOH).

$$K_{a1} = \frac{[H_3O^+][HA^-]}{[H_2A]}$$

$$K_{a2} = \frac{[H_3O^+][A^{2-}]}{[HA^-]}$$

If the K_a values for a multiprotic acid are distinct enough, then two equivalence points appear in a titration curve. But if the K_a values are too close, the multiprotic acid will not show titration curves with multiple equivalence points.

For example, fumaric acid has two acidic hydrogen atoms with the following K_a values:

$$K_{a1} = 9.33 \times 10^{-4}, \quad pK_{a1} = 3.03$$

$$K_{a2} = 3.63 \times 10^{-5}, \quad pK_{a2} = 4.44$$

where "1" and "2" refer to the first and second acidic hydrogen ions.

When fumaric acid is titrated, both acidic protons detach at nearly the same time and the two equivalence points are not easily detected. Usually the equivalence points show up as a single equivalence point somewhere between the two values.

Applying Your Knowledge – Determine the Amount of Acetylsalicylic acid in Aspirin

You will be given one solid aspirin tablet. Use titration to see if you can identify the acid in aspirin as acetylsalicylic acid based on the K_a value(s) and to determine if the amount of acetylsalicylic acid in the tablet matches the amount on the manufacturer's label.

NOTE: Acetylsalicylic acid is a weak acid and doesn't dissolve well. Therefore, for the titration, use a piece of the aspirin of approximately 0.1 g.

Before you perform the experiment, research and determine the following:

- How much acetylsalicylic acid is reported to be in one aspirin tablet, according to the bottle?

  325 mg (Answers may vary, depending on the particular bottle of aspirin.)

- What is the percentage of acetylsalicylic acid in your aspirin?

$$\frac{325 \text{ mg acetylsalicylic acid}}{374 \text{ mg aspirin}} \times 100 = 86.89\%$$

Answers will vary, but they should be close to 90%.

- Being a weak acid, acetylsalicylic acid can be difficult to dissolve. Use approximately 0.1 g of aspirin for the titration. From the mass you measured, calculate the amount of acetylsalicylic acid in your sample.

0.1200 g aspirin $\times$ 0.8689 = 0.1043 g acetylsalicylic acid

- List observations that indicate the aspirin has fully dissolved.

Lack of cloudiness in the solution.

No solid at the bottom of the flask.

No solid moving in the solution as it is stirred.

- What is the molecular formula and molar mass of acetylsalicylic acid?

Molecular formula: $C_9H_8O_4$

Molecular mass: 180.157 g/mole

- Is acetylsalicylic acid monoprotic or polyprotic?

Monoprotic

- What are the equation(s) for the reaction(s) between acetylsalicylic acid and sodium hydroxide?

$C_9H_8O_4 + NaOH \rightarrow NaC_9H_7O_4 + H_2O$
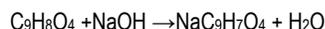
- Based on the literature value(s) of K_a for acetylsalicylic acid, how many equivalence points will you expect to see, and what are the value(s)?

Acetylsalicylic acid has one equivalence point: $K_a = 3.27 \times 10^{-4}$

After you have performed the experiment and collected your data, determine the percentage of error for K_a. Also determine the percentage difference in the reported mass of acetylsalicylic acid in one tablet and the experimental value based on your titration. Finally, identify at least three sources of error for your data.

Based on sample data, the equivalence point occurs at 1.47 mL. At the half-equivalence point of 0.735 mL, the pH = 3.70, so the $pK_a = 3.70$ and the $K_a = 2.00 \times 10^{-4}$. The percentage of error is

$$\text{Percent error} = \frac{|\text{Theoretical Value} - \text{Experimental Value}|}{\text{Theoretical Value}} \times 100$$

$$\text{Percent error} = \frac{|3.27 \times 10^{-4} - 2.00 \times 10^{-4}|}{3.27 \times 10^{-4}} \times 100 = 38.8\%$$

Knowing the volume of NaOH needed to reach the equivalence point, the number of grams of acetylsalicylic acid can be determined:

$$\frac{1.47 \text{ mL NaOH}}{1} \times \frac{0.50 \text{ mol NaOH}}{L} \times \frac{1 \text{ L}}{1000 \text{ mL}} = 7.35 \times 10^{-4} \text{ mol NaOH, so there are } 7.35 \times 10^{-4} \text{ mol acetylsalicylic acid}$$

$$\frac{7.35 \times 10^{-4} \text{ mol acetylsalicylic acid}}{1} \times \frac{180.157 \text{ g}}{1 \text{ mol acetylsalicylic acid}} = 0.132 \text{ g acetylsalicylic acid}$$

The percentage difference in the mass specified on the bottle versus the experimental value is

$$\frac{|0.104 \text{ g specified} - 0.132 \text{ g experimental}|}{0.104 \text{ g specified}} \times 100 = 26.9\%$$

Sources of error are:

  The aspirin tablet may not have had 325 mg of acetylsalicylic acid.

  Incomplete dissolution of the aspirin.

  Incomplete transfer of aspirin from the weighing boat to the solution.

  Miscalibration of either the pH sensor or drop counter.

  Non-uniform drop size.

Teacher Tips

Tip 1 – Sodium hydroxide solutions

It is best to use freshly made sodium hydroxide solutions for this procedure, as sodium hydroxide in solution can precipitate out over time.

Tip 2 – Calibrating the drop counter

If the drop counter has been disconnected from the data collection system between titrations, students will need to calibrate it before carrying out the titration. The calibration procedure is in Appendix A.

15. INTRODUCTION TO BUFFERS

Initial Question

As you have seen in titration experiments, adding one drop of an acidic or basic solution to another solution can result in large changes in pH. However, many biological reactions only work within a narrow range of pH (between about 6 and 8). How does the body, a plant, or the soil keep the pH from changing drastically every time it comes in contact with an acid or base? In this lab, you will investigate solutions that help answer this question.

What is a buffer and what are the components of a buffer solution?

Learning Objectives[*]

Students create and analyze a buffer system.

LO 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.

SP 1.4 / Students can *use representations and models* to analyze situations or solve problems qualitatively and quantitatively.

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

Time Requirement

Preparation time: 60 minutes / Lab activity: 90 minutes

Materials and Equipment

Model 1

- Data collection system
- pH sensor[1]
- Beaker (glass), 50-mL
- Graduated cylinder 25-mL
- Acetic acid (CH_3COOH), 20 mL[2]

- Sodium acetate ($NaCH_3COO$) approx. 1 g
- Stirring rod
- Scoopula™ spatula
- Materials for pH sensor calibration (refer to Appendix A)

[1]Included with PASCO Advanced Chemistry Sensor.

[2]Use full-strength white vinegar.

Model 2

- Data collection system
- pH sensor[1]
- Beakers (5), 50-mL
- Graduated cylinder, 25-mL
- Graduated cylinder, 10-mL or volumetric pipet, 5-mL
- Solution 1: Distilled water, 20 mL
- Solution 2: 0.01 M Acetic acid (CH_3COOH), 20 mL[2]

- Solution 3: 0.01 M Acetic acid (CH_3COOH) and 0.01 M Sodium acetate ($NaCH_3COO$), 20 mL[2]
- Solution 4: 0.01 M Sodium bisulfate ($NaHSO_3$) and 0.01 M Sodium sulfate (Na_2SO_3), 20 mL[2]
- Solution 5: 0.01 M Sodium bicarbonate ($NaHCO_3$) and 0.01 M Sodium carbonate (Na_2CO_3), 20 mL[2]
- 0.01 M Sodium hydroxide (NaOH), 25 mL[2]
- Stirring rod
- Wash bottle

[1]Included with PASCO Advanced Chemistry Sensor.

[2]To formulate these solutions using 1.0 M Acetic acid, sodium bisulfate, sodium bicarbonate, and sodium hydroxide, refer to the Lab Preparation section.

Applying Your Knowledge

- Data collection system
- pH sensor
- Beakers (2), 100-mL
- Stirring rod

- Bufferin™ tablet, 325 mg
- Aspirin tablet, 325 mg
- Mortar and pestle
- Distilled water, 100 mL

Prerequisites

Students should be familiar with the following concepts:

- Acid–base reactions
- Equilibrium
- Le Châtelier's Principle
- K_a and pK_a equations

Lab Preparation

These are the materials and equipment to set up prior to the lab:

Model 1

1. **Acetic acid:** Supply students with full strength white vinegar (~20 mL per group). Label it "Acetic Acid—Model 1."

Model 2

2. **1.0 M Sodium hydroxide (NaOH):** Prepare 1000 mL of 1.00 M sodium hydroxide (NaOH) by placing 39.99 g of solid NaOH in a 1000-mL volumetric flask 1/3 full of distilled water. Stir it well and let it sit to cool. When the solid has completely dissolved, fill the flask to the line with distilled water.

   a. **0.01 M Sodium hydroxide (NaOH):** Prepare 1000 mL of 0.01 M NaOH by placing 10.0 mL of the 1.0 M NaOH in a 1-L volumetric flask and fill the flask to the line with distilled water. This is used for preparing the buffers and for student use.

3. The following prepare 1 liter of each buffer solution, enough for 25 student groups or individuals.

   NOTE: All solutions below, except for Solution 2, 0.01 M CH$_3$COOH, are formed by mixing 0.02 moles of acid + 0.01 moles NaOH. This results in a 0.01 M solution of acid and a 0.01 M solution of conjugate base. Solution 1 is distilled water.

   a. **0.01 M Acetic acid (CH$_3$COOH):** Place about 100 mL of distilled water in a 1-L volumetric flask. Add 10.0 mL of 1.0 M acetic acid. Fill the flask to the line with additional distilled water. Label this "Solution 2."

   b. **0.01 M Acetic acid (CH$_3$COOH) and 0.01 M Sodium acetate (NaCH$_3$COO):** Place about 100 mL of distilled water in a 1-L volumetric flask. Add 20.0 mL of 1.0 M acetic acid and then add 10 mL of 1.0 M sodium hydroxide (NaOH). Fill the flask to the mark with additional distilled water. Label this "Solution 3."

   c. **0.01 M Sodium bisulfate (NaHSO$_3$) and 0.01 M Sodium sulfate (Na$_2$SO$_3$):** Place about 100 mL of distilled water in a 1-L volumetric flask. Add 2.075 g of sodium bisulfite and then add 10 mL of 1.0 M sodium hydroxide. Fill the flask to the mark with additional distilled water. Label this "Solution 4."

   d. **0.01 M Sodium bicarbonate (NaHCO$_3$) and 0.01 M Sodium carbonate (Na$_2$CO$_3$):** Place about 100 mL of distilled water in a 1-L volumetric flask. Add 1.680 g of sodium bicarbonate and then add 10 mL of 1.0 M sodium hydroxide. Fill the flask to the mark with additional distilled water. Label this "Solution 5."

   Summary of buffer solution preparation: Place about 100 mL of distilled water in a 1-L volumetric flask. Add Compound 1 and then Compound 2. Fill to the mark with additional distilled water.

Summary of solution preparation

Solution	Compound 1	Compound 2	Product
2	12.0 mL of vinegar (0.83 M) or 10.0 mL of 1.0 M acetic acid	None	0.01 M CH$_3$COOH
3	24.0 mL of vinegar (0.83 M) or 20.0 mL of 1.0 M acetic acid	10 mL of 1.0 M NaOH	0.01 M CH$_3$COOH with 0.01 M NaCH$_3$COO
4	2.075 g of NaHSO$_3$	10 mL of 1.0 M NaOH	0.01 M NaHSO$_3$ with 0.01 M Na$_2$SO$_3$
5	1.680 g of NaHCO$_3$	10 mL of 1.0 M NaOH	0.01 M NaHCO$_3$ with 0.01 M Na$_2$CO$_3$

Safety

Add these important safety precautions to your normal laboratory procedures:

- Wear goggles and work carefully to prevent spills

- Sodium hydroxide is corrosive. If you come in contact with it, flush the exposed area with large amounts of water.

Getting Your Brain in Gear

The Brønsted–Lowry Acid–Base Theory expands on the Acid–Base Theory of Svante Arrhenius. The Arrhenius theory is easy to use but covers a limited number of substances. Brønsted and Lowry developed a theory that includes far more. When discussing strong acids and bases, it is common practice to use the Arrhenius theory. When weak acids are involved, the Arrhenius theory is not always sufficient and other theories must be used.

1. What are the definitions of acids and bases according to Arrhenius?

    a. Acids

       Acids create hydrogen ions in water.

    b. Bases

       Bases create hydroxide ions in water.

2. What are the definitions of acids and bases according to Brønsted and Lowry?

    a. Acids

       Acids are proton donors.

    b. Bases

       Bases are proton acceptors.

3. According to the Brønsted–Lowry theory, when acids and bases are combined, they react to form conjugate acid–base pairs. When weak acids and bases react, water often becomes a reactant. For items "a" and "b," add the labels "Acid" and "Base" to the appropriate molecule indicated by the bracket. For "c" and "d," first draw the brackets and then label the acid and base pairs.

    Example:
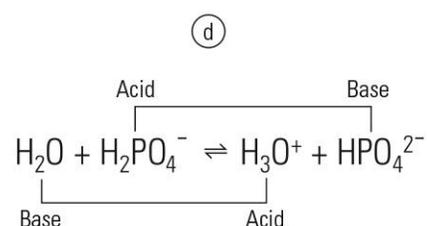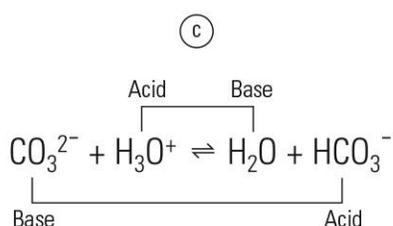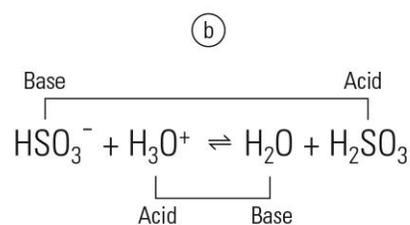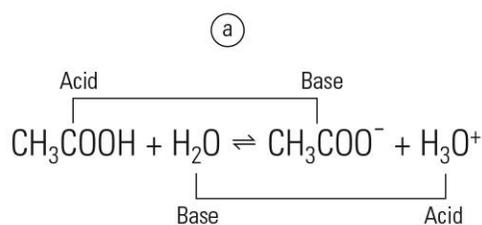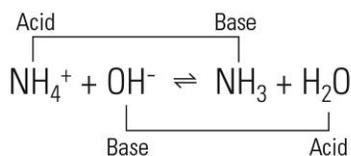
e. What is different between the components of a conjugate acid–base pair?

The acid and conjugate base or base and conjugate acid differ by a proton (H^+).

4. In this lab, you will be working with mixtures of solutions, such as acetic acid (CH_3COOH) mixed with sodium acetate ($NaCH_3COO$).

a. Write the net ionic equation for the reaction of $NaCH_3COO$ and CH_3COOH.

NOTE: Water is a reactant.

Because CH_3COOH is a weak acid and $NaCH_3COO$ contains its conjugate base, the best answer is

$$CH_3COOH\ (aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + CH_3COO^-\ (aq)$$
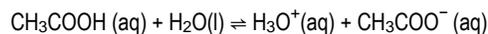
However, many students will, on their first attempt, write:

$$CH_3COOH\ (aq) + NaCH_3COO\ (aq) \rightarrow NaCH_3COO\ (aq) + CH_3COOH\ (aq)$$
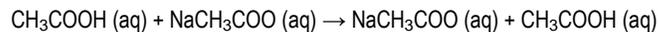
The point of this question is not for students to get it correct before the lab. The point is to see if their predicted reaction matches their observations in the lab.

b. In the beaker below, draw a particulate-level representation showing what the $NaCH_3COO$ and CH_3COOH solution looks like at the molecular level. You do not need to explicitly represent the water molecules. Use the particulate key as a guide.
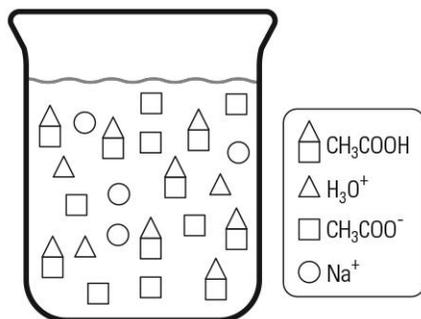
Ideally, the drawing should contain CH_3COOH molecules, Na^+ ions and CH_3COO^- ions. Some students might think to include the H^+ or H_3O^+ ions, but for now the important thing is that they recognize the species that are in the solution.

c. What is the conjugate acid of CH_3COO^-?

CH_3COOH

Model 1

Building Model 1 − Observing a Reaction System

1. Add 20 mL of acetic acid to a 50-mL beaker.

2. Calibrate the pH sensor.

    NOTE: You will need to re-calibrate the pH sensor for the other procedures if they are carried out in a different class period.
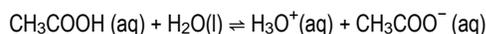
3. Measure the pH of the acetic acid solution and record the value in the Model 1 Data Table.

    NOTE: Make sure the glass bulb of the pH sensor is covered with solution.

4. Add a *pea size* amount of solid sodium acetate to the beaker. Use a stirring rod or gently swirl the solution until the sodium acetate dissolves.

❷ 5. Based on your reaction equation in the Getting Your Brain in Gear section, should the addition of $NaCH_3COO$ make the solution's pH increase, decrease or remain the same? Justify your answer.

    Students who recognized the solution is in equilibrium should, using Le Châtelier's principle, correctly predict that the solution's pH will increase because the reaction will shift to the left; hydronium ions (hydrogen ions) will be consumed.

$$CH_3COOH\ (aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + CH_3COO^-\ (aq)$$

6. Measure the pH of the solution and record the value in the Model 1 Data Table.

Model 1 − Observing a Reaction System

Table 1: Model 1 Data Table–pH change in acetic acid due to added sodium acetate

Solution	pH
Acetic acid	2.3
Acetic acid and sodium acetate	3.1

Analyzing Model 1 − Observing a Reaction System

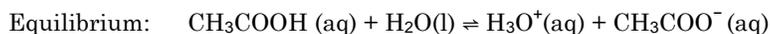7. Did the pH of the solution increase, decrease, or remain the same?

    The pH increased.

8. a. Does $NaCH_3COO$ dissociate in water?

    Yes.

    b   How should the dissociation be represented in water, as $NaCH_3COO$ (aq) or $Na^+(aq) + CH_3COO^-(aq)$?

    It should be represented as: $Na^+(aq) + CH_3COO^-(aq)$. Alkali metals and acetates are always soluble.

9. Two possible reaction equations are shown below.

   Equilibrium: $CH_3COOH (aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + CH_3COO^- (aq)$

   Stoichiometric addition: $CH_3COOH (aq) + NaCH_3COO(aq) \rightarrow NaCH_3COO (aq) + CH_3COOH (aq)$

   Which of these reaction equations best explains the change in the pH observed? Justify your answer.

   The equilibrium reaction best explains the observation because the addition of acetate results in the reaction shifting left, consuming H_3O^+ ions.

10. Why is the Na^+ ion not shown in the equilibrium reaction?

    It is a spectator ion.

11. You answered the following questions in the Getting your Brain in Gear section. Revise your answer, if necessary, with the new information from Model 1.

    In this lab, you will be working with mixtures of solutions, such as acetic acid (CH_3COOH) mixed with sodium acetate ($NaCH_3COO$).

    a. Write a net ionic equation for the reaction of $NaCH_3COO$ and CH_3COOH.

       NOTE: Water is a reactant.

       Because CH_3COOH is a weak acid and $NaCH_3COO$ contains its conjugate base, the equation is
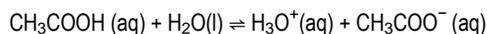
       $$CH_3COOH (aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + CH_3COO^- (aq)$$

    b. In the beaker below, draw a particulate-level representation showing what the $NaCH_3COO$ and CH_3COOH solution looks like at the molecular level. You do not need to explicitly represent the water molecules. Use the particulate key as a guide.
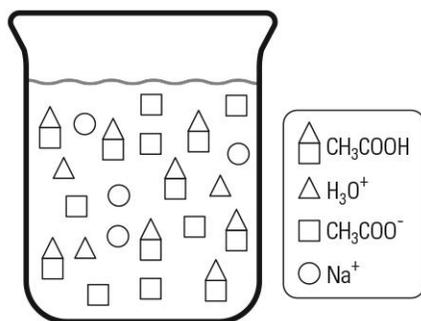
    The drawing should contain CH_3COOH molecules, Na^+ ions, and CH_3COO^- ions.

MODEL 2

Building Model 2 – Observing the pH of Solutions

1. Using a graduated cylinder, measure 20 mL of each of the following five solutions into 50-mL beakers.

Table 2: Solutions to test

Solution #	Solution
1	Distilled water
2	0.01 M Acetic acid (CH_3COOH)
3	0.01 M Acetic acid (CH_3COOH) and 0.01 M Sodium acetate ($NaCH_3COO$)
4	0.01 M Sodium bisulfate ($NaHSO_3$) and 0.01 M Sodium sulfate (Na_2SO_3)
5	0.01 M Sodium bicarbonate ($NaHCO_3$) and 0.01 M Sodium carbonate (Na_2CO_3)

2. Measure the initial pH of each solution and record the results in the Model 2 Data Table.

   NOTE: Make sure the glass bulb at the bottom of the pH meter is covered with solution.

3. Using a graduated cylinder or volumetric pipet, add 5.0 mL of 0.01 M NaOH(aq) to each of the five solutions. Swirl each beaker gently and then measure and record the pH.

   Students should observe very small changes in pH for the buffers (on the order of 0.1 or 0.2 pH units), slightly greater changes for a weak acid like acetic acid, and large changes (> 3 pH units) for water.

### Model 2 – Observing the pH of Solutions

Table 3: Model 2 Data Table–Compare pH after adding 0.01 M NaOH

Solution Number	Solution	Initial pH	pH after Adding Base
1	Distilled water	5.0	11.7
2	0.01 M Acetic acid (CH_3COOH)	3.1	3.8
3	0.01 M Acetic acid (CH_3COOH) and 0.01 M Sodium acetate ($NaCH_3COO$)	4.4	4.6
4	0.01 M Sodium bisulfate ($NaHSO_3$) and 0.01 M Sodium sulfate (Na_2SO_3)	6.9	7.1
5	0.01 M Sodium bicarbonate ($NaHCO_3$) and 0.01 M Sodium carbonate (Na_2CO_3)	10.4	10.8

Analyzing Model 2 – Observing the pH of Solutions

4. a. Which solution had the greatest change in pH?

    Solution 1.

    b. Which solution had the least change in pH?

    Solutions 3, 4, and 5.

5. A *buffer* is a solution that, upon addition of acid or base, does not have a large change in pH. Which of your solutions are buffers?

    Solutions 3, 4, and 5 are buffers.

6. How are the two compounds present in each buffer solution related to one another?

    All buffers contain a weak acid and an ionic compound (salt) that contains the conjugate base of the weak acid.

7. Consider a buffer solution formed from 0.1 M HF and 0.1 M NaF.

    NOTE: NaF is soluble.

    a. What FOUR species, besides water, are extensively present in solution? (Hint: the 4th one is from the dissociation of HF.)

    HF, Na^+, F^-, and H_3O^+ (from the dissociation of HF)

    b. Which of these ions is present as a spectator ion?

    Na^+ is the spectator ion.

    c. What equilibrium exists for the remaining ions?

    $HF (aq) + H_2O(l) \rightleftharpoons H_3O^+ (aq) + F^- (aq)$

8. a. If a compound containing H^+ is added to this solution, what direction will the equilibrium reaction shift and what species is consumed in the process?

    The reaction will shift to the left, consuming F^- in the process.

    b. Why is it necessary, then, to have NaF as well as HF present for this solution to behave as a buffer?

    The NaF provides the F^- ion that reacts with the added hydrogen ions to produce HF, minimizing the pH change that would otherwise result from the added acid.

9. a. If a compound containing OH^- ions is added to this solution, what reaction will occur?

    $OH^- + H^+ \rightarrow H_2O$

    b. What direction will the equilibrium reaction shift and what species is consumed in the process?

    The reaction shifts to the right, to replace H^+, consuming HF in the process.

    c. Why, then, is it necessary to have HF as well as NaF present for this solution to behave as a buffer?

    The solution must have HF to consume bases that are added and F^- to consume acids that are added.

10. The equilibrium reaction equation for the acetic acid/acetate buffer system is:

$$CH_3COOH(aq) + H_2O(l) \rightleftharpoons H_3O^+ (aq) + CH_3COO^-(aq)$$
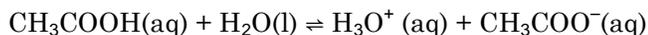
a. Using the equilibrium reaction, explain why the pH changes only a little when a small amount of HCl is added.

The equilibrium will shift to the left, converting the added H^+ to H_2O, which keeps the pH nearly the same.

b. Using the equilibrium reaction, explain why the pH changes only a little if a small amount of NaOH is added to the buffer system above.

The added OH^- neutralizes H_3O^+, so the reaction shifts to the right to replace the neutralized H_3O^+, which keeps the pH nearly the same.

11. Record the initial pH from the corresponding buffer systems in Model 2 in Table 4.

Table 4: Buffer systems

Solution Number	Buffer Solution Components	Initial pH	pK_a
3	0.01 M Acetic acid (CH_3COOH) and 0.01 M Sodium acetate ($NaCH_3COO$)	4.4	4.7
4	0.01 M Sodium bisulfate ($NaHSO_3$) and 0.01 M Sodium sulfate (Na_2SO_3)	6.9	7.0
5	0.01 M Sodium bicarbonate ($NaHCO_3$) and 0.01 M Sodium carbonate (Na_2CO_3)	10.4	10.3

12. Chemists often characterize acids by their pK_a. The pK_a is defined as

$$pK_a = -\log(K_a)$$

The K_a of each of the acids and bases used in the buffers in Model 1 are given below. Calculate the pK_a for each and record them in Table 4.

acetic acid	$CH_3COOH (aq) \rightleftharpoons H^+(aq) + CH_3COO^-(aq)$	$K_a = 1.8 \times 10^{-5}$
bisulfite	$HSO_3^- (aq) \rightleftharpoons H^+(aq) + SO_3^{2-}(aq)$	$K_a = 1.0 \times 10^{-7}$
bicarbonate	$HCO_3^- (aq) \rightleftharpoons H^+(aq) + CO_3^{2-}(aq)$	$K_a = 5.6 \times 10^{-11}$

Sample calculation:

$pK_a = -\log(1.8 \times 10^{-5}) = 4.7$

13. Identify a relationship between the pK_a of the acids and bases and the pH of the buffer solutions.

They have similar values.

14. Use a reference source to find an acid that will be the foundation of a buffer solution with a pH of 6.5.

To identify an acid with a K_a corresponding to a pK_a close to 6.5, use the relationship $pK_a = -\log(K_a)$:

$6.5 = -\log(K_a)$; $K_a = 3.16 \times 10^{-7}$; citric acid ($H_3C_6H_5O_7$) has a $K_a = 3.2 \times 10^{-7}$.

15. Suggest a compound that will provide a conjugate base for the acid you chose in the previous question.

Sodium citrate ($NaH_2C_6H_5O_7$) can be used with $H_3C_6H_5O_7$. However any soluble cation–citrate ion solution will work.

Connecting to Theory

Looking at a weak acid–strong base titration curve, you will find a region of the curve that is nearly flat in the acidic region. This occurs because, with this combination of reagents, a buffer solution has been created. As OH^- is added to a weak acid, the conjugate base is formed. The buffer solution created resists changes in pH, causing this region of the curve to appear relatively flat.
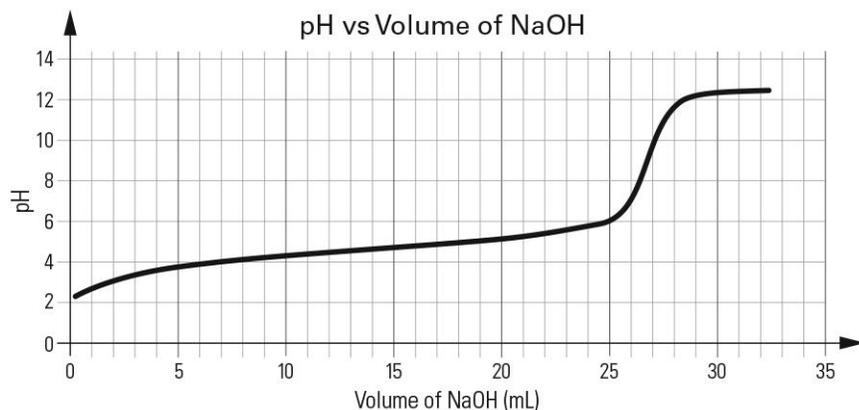
Applying Your Knowledge – Determining the Buffering Ability of Bufferin™

1. Obtain one 325 mg tablet of aspirin and a 325 mg tablet of Bufferin. Crush each tablet and place them in separate beakers containing 50 mL of distilled water. Stir until they are dissolved.

2. Measure and record the pH of each solution.

    Table 5: Comparison of aspirin and Bufferin

Sample	pH
Aspirin	2.30
Bufferin	5.53

3. Record the active ingredients from the bottles of the two tablets you examined.

    Aspirin contains aspirin plus inactive ingredients. Bufferin contains aspirin "buffered with magnesium carbonate, calcium carbonate and magnesium oxide."

4. Using words and reaction equations, explain the observed data.

    Any of the three extra ingredients of Bufferin will act as bases toward aspirin ($HC_9H_7O_4$), creating the conjugate base of aspirin and thus a buffer.

    For example: $HC_9H_7O_4 + CO_3^{2-} \rightleftharpoons C_9H_7O_4^- + HCO_3^-$

Teacher Tips

Tip 1 – Have students perform both buffer labs

This manual has two labs that address the concept of buffers: Introduction to Buffers and Buffer Properties. The focus of Buffer Properties, buffer capacity, is the culmination of the Introduction to Buffers activity, so students will benefit if the two labs are carried out as if they were two parts of the same lab.

Tip 2 − Dispelling misconceptions

The point of Model 1 is to dispel a misconception that an acid and a salt containing its conjugate base react in a stoichiometric addition rather than form an equilibrium reaction system. Allow students to give the wrong answer to the Getting Your Brain in Gear questions.

Tip 3 – Solution preparation

The solution preparation for this lab can be time consuming. However, the solutions store well, so depending on the number of students groups you have, you may have plenty of excess for subsequent years. To reduce the time involved, you might want to assign your students solutions to prepare for the entire class. This is good practice with solution making.

Tip 4 – pH of distilled water

Students are often confused, or convinced that their sensors are incorrect when the pH of distilled (or even deionized) water is not 7.0. It is worth reminding students that even the smallest amount of acid or base present as a contaminant can cause the pH to shift up or down by 2 or more pH units. The most common contaminant, if you are using water that is not freshly deionized or distilled, is dissolved CO_2, which makes the pH of the water 5 or less.

Tip 5 – Alka-Seltzer™

Alka-Seltzer is a well-known and frequently used buffer solution. It was not used in this lab because the buffering reaction system is extremely complicated; all of the citric acid is consumed, making the citrate and bicarbonate ions the principle ions present at equilibrium. It was preferable in this lab that students study buffers for which they could write simpler reaction equations. However, the Alka-Seltzer system is worth studying and discussing as an extension of this lab.

16. BUFFER PROPERTIES

Initial Question

Buffers are solutions that are resistant to changes in their pH when acids or bases are added. For example, human blood contains the bicarbonate ion. This ion can accept hydrogen ions to remove excess acidity in the blood or can donate hydrogen ions to remove alkalinity in the blood. Once the bicarbonate ions are used up, blood can rapidly become either too acidic or too basic. In other words, the bicarbonate buffer system in blood has a limited capacity.

How are buffers made, and what determines their capacity?

Learning Objectives[*]

Students analyze the nature of buffers as they prepare buffer solutions of a specified pH and test their efficacy.

LO 6.18 / The student can design a buffer solution with a target pH and buffer capacity by selecting an appropriate conjugate acid-base pair and estimating the concentrations needed to achieve the desired capacity.

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

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

Time Requirement

Preparation time: 60 minutes / Lab activity: 90 minutes

Materials and Equipment

Model 1

- Data collection system
- pH sensor[1]
- Analytical balance
- Volumetric flask, 100-mL or 250-mL[2]
- Beakers (2), glass, 50-mL
- Sodium acetate (NaCH$_3$COO), about 1.0 g[3]

- Ammonium chloride (NH$_4$Cl), about 1.0 g[3]
- 0.3 M Acetic acid (CH$_3$COOH), 100 mL[3]
- 0.3 M Ammonia (NH$_3$), 100 mL[3,4]
- Distilled water, 150 mL[3]
- Marking pen

[1]Included with PASCO Advanced Chemistry Sensor.

[2]The volume of the flask depends on the buffer assigned from the Model 1 Data Table.

[3]The volume and mass needed depends on the buffer assigned from the Model 1 Data Table.

[4]To formulate the 0.3 M ammonia from ammonium hydroxide (NH$_4$OH), refer to the Lab Preparation section.

Model 2

- Universal indicator, 3 drops
- Beral pipets (2)
- Test tubes (3), 20 mm × 150 mm, glass, 25-mL
- 0.10 M Hydrochloric acid (HCl), 20 mL

- 0.10 M Sodium hydroxide (NaOH), 20 mL
- Buffer solution from Model 1
- Distilled and deionized water

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Applying Your Knowledge

- Data collection system
- pH sensor[1]
- Beakers (2), 50-ml
- Volumetric flask, 100-ml
- Two of the following, to create 100 mL of buffer:

  0.3 M Acetic acid (CH_3COOH)

  0.3 M Sodium acetate ($NaCH_3COO$)

  0.3 M Sodium phosphate dibasic (Na_2HPO_4)

- 0.3 M Sodium phosphate monobasic (NaH_2PO_4)
- 0.3 M Ammonia (NH_3)[2]
- 0.3 M Ammonium chloride (NH_4Cl)
- 0.3 M Potassium phosphate (K_3PO_4)
- 0.3 M Phosphoric acid (H_3PO_4)
- 6 M Sodium hydroxide (NaOH), 5 drops[3]
- 6 M Hydrochloric acid (HCl), 5 drops[3]
- Stirring rod

[1]Included with PASCO Advanced Chemistry Sensor.

[2]To formulate the 0.3 M ammonia from ammonium hydroxide (NH_4OH), refer to the Lab Preparation section.

[3]Your teacher will add the 5 drops of NaOH and HCl to test your buffer.

Prerequisites

Students should be familiar with the following concepts:

- Acid–Base Theory
- Buffers
- Brønsted–Lowry Acid–Base theory
- Conjugate Acids and Bases

Lab Preparation

These are the materials and equipment to set up prior to the lab:

NOTE: In Model 1, students prepare the twelve buffers in the Model 1 Data Table. Assign one buffer to each student group so all buffers are formulated. In Model 2, students share the data for the buffers they haven't prepared. Check that the results are reasonable before students complete the Analyzing Model 2 section.

Model 1

1. **0.3 M Ammonia (NH_3):** Prepare 1000 mL of 0.3 M ammonium hydroxide (NH_4OH) by filling a 1000 mL volumetric flask 1/3 full of distilled water. Add 10.514 g ammonium hydroxide to the flask and swirl to dissolve. Fill the flask to the line with distilled water. Label this solution "0.3 M NH_3."

Model 1 and Applying Your Knowledge

2. **0.3 M Acetic acid (CH_3COOH):** Prepare 1000 mL of 0.3 M acetic acid (CH_3COOH) by filling a 1000-mL volumetric flask 1/3 full of distilled water. Add 17.24 mL of 17.4 M glacial acetic acid to the flask and swirl to dissolve. Fill the flask to the line with distilled water. This solution will be used in both Model 1 and the Applying Your Knowledge; you will need two liters.

Model 2

3. **0.1 M Hydrochloric acid (HCl):** Prepare 1000 mL of 0.1 M hydrochloric acid (HCl) by filling a 1000-mL volumetric flask 1/3 full of distilled water. Add 8.33 mL of 12.0 M hydrochloric acid to the flask and swirl to dissolve. Fill the flask to the line with distilled water.

4. **0.1 M Sodium hydroxide (NaOH):** Prepare 1000 mL of 0.1 M sodium hydroxide (NaOH) by filling a 1000-mL volumetric flask 1/3 full of distilled water. Add 3.999 g of sodium hydroxide to the flask and swirl to dissolve. Fill the flask to the line with distilled water.

Applying Your Knowledge

NOTE: The components listed can be combined to create five different buffers, each with a different pH value. Assign one of the five pH value to each student group so all buffers are formulated.

5. **0.3 M Ammonium chloride (NH₄Cl):** Prepare 1000 mL of 0.3 M ammonium chloride (NH_4Cl) by filling a 1000-mL volumetric flask 1/3 full of distilled water. Add 16.047 g of ammonium chloride to the flask and swirl to dissolve. Fill the flask to the line with distilled water.

6. **0.3 M Ammonia (NH₃):** Prepare 1000 mL of 0.3 M ammonia (NH_3) by filling a 1000-mL volumetric flask 1/3 full of distilled water. Add 10.514 g of ammonium hydroxide to the flask and swirl to dissolve. Fill the flask to the line with distilled water. Label this solution as 0.3 M NH_3 to avoid confusion.

7. **0.3 M Phosphoric acid (H₃PO₄):** Prepare 1000 mL of 0.3 M phosphoric acid (H_3PO_4) by filling a 1000-mL volumetric flask 1/3 full of distilled water. Add 20.27 mL of 14.8 M phosphoric acid to the flask and swirl to dissolve. Fill the flask to the line with distilled water.

8. **0.3 M Sodium phosphate dibasic (Na₂HPO₄)**: Prepare 1000 mL of 0.3 M sodium phosphate dibasic (Na_2HPO_4) by filling a 1000-mL volumetric flask 1/3 full of distilled water. Add 42.588 g of sodium phosphate dibasic to the flask and swirl to dissolve. Fill the flask to the line with distilled water. This solution will be used for two different buffers in the Applying Your Knowledge section, so you may need two liters.

9. **0.3 M Sodium phosphate monobasic (NaH₂PO₄):** Prepare 1000 mL of 0.3 M sodium phosphate monobasic (NaH_2PO_4) by filling a 1000-mL volumetric flask 1/3 full of distilled water. Add 35.993 g of sodium phosphate monobasic to the flask and swirl to dissolve. Fill the flask to the line with distilled water. This solution will be used for two different buffers in the Applying Your Knowledge section.

10. **0.3 M Potassium phosphate tribasic (K₃PO₄):** Prepare 1000 mL of 0.3 M potassium phosphate (K_3PO_4) by filling a 1000-mL volumetric flask 1/3 full of distilled water. Add 63.680 g of potassium phosphate to the flask and swirl to dissolve. Fill the flask to the line with distilled water.

11. **0.3 M Sodium acetate (NaCH₃COO):** Prepare 1000 mL of 0.3 M sodium acetate ($NaCH_3COO$) by filling a 1000-mL volumetric flask 1/3 full of distilled water. Add 24.610 g of sodium acetate to the flask and swirl to dissolve. Fill the flask to the line with distilled water.

12. **6.0 M Sodium hydroxide (NaOH):** Prepare 1000 mL of 6.0 M sodium hydroxide (NaOH) by filling a 1000-mL volumetric flask 1/3 full of distilled water. Add 239.982 g of sodium hydroxide to the flask and swirl to dissolve. Let it sit to cool. Fill the flask to the line with distilled water. The creation of this solution is exothermic. It will get very hot.

13. **6.0 M Hydrochloric acid (HCl):** This dilution is exothermic; add the acid in small increments, allowing the solution to cool between increments. To prepare 1000 mL of 6.0 M hydrochloric acid (HCl), fill a 1000-mL volumetric flask 1/3 full of distilled water. Add 500.00 mL of concentrated hydrochloric acid to the flask and swirl to dissolve. Fill the flask to the mark with distilled water.

Safety

Add these important safety precautions to your normal laboratory procedures:

- Wear your goggles.

- This lab uses strong acids and bases. If you come in contact with either of them, flush the area with plenty of water.

Getting Your Brain in Gear

1. For each solution described below, determine if it acts as a buffer. Explain your reasoning.

    a. 0.50 mole of HCl and 0.50 mole of NaCl in 250 mL of water

    No, this is not a buffer. HCl is a strong acid.

    b. 0.50 mole of HNO_2 and 0.50 mole of $NaNO_2$ in 250 mL of water

    Yes, this solution contains a weak acid and the salt of its conjugate base, so it will act as a buffer.

    c. 1.00 mole of CH_3COOH and 0.50 mole NaOH in 250 mL of water

    Yes, the NaOH will react with some of the weak acid to create its conjugate base.

2. Consider a buffer made of an equal number of moles of HF and NaF.

    a. Write a net ionic equation to illustrate how the buffer solution reacts to keep the pH stable when strong acid is added.

    $F^- + H_3O^+ \rightleftharpoons HF + H_2O$

    b. Write a net ionic equation to illustrate how the buffer solution reacts to keep the pH stable when strong base is added.

    $HF + OH^- \rightleftharpoons F^- + H_2O$

MODEL 1

Building Model 1 – Buffer Preparation

1. After your instructor assigns you a buffer from Model 1 to prepare, refer to the Model 1 Data Table to determine the chemicals and the molarities you will need for your buffer.

   Solution assigned: _____

❷ 2. What component(s) of your assigned buffer system are available (refer to the Materials and Equipment list for Model 1)?

   For solutions 1 to 5: 0.3 M ammonia and ammonium chloride.

   For solutions 6 to 10: 0.3 M acetic acid and sodium acetate.

❷ 3. Calculate the number of moles of weak acid and conjugate base, or weak base and conjugate acid, you will need in the final solution to make the buffer you have been assigned.

   For any of the 0.15 M, 0.10 M and 0.05 M solutions, the following number of moles is needed, respectively:

   $0.15\ M \times 0.100\ L = 0.015$ moles

   $0.10\ M \times 0.100\ L = 0.010$ moles

   $0.05\ M \times 0.100\ L = 0.005$ moles

❷ 4. Calculate the mass of the solid and volume of solution you will need to make your assigned buffer.

   Sample calculation to determine the mass for 100 mL of 0.15 M sodium acetate needed:

   $$\frac{0.015\ mol}{1} \times \frac{82.0337\ g}{1\ mol} = 1.231\ g\ \text{sodium acetate}$$

   Sample calculation to determine the volume of 0.15 M acetate acid or 0.15 M ammonia needed:

   $$M_1 \times V_1 = M_2 \times V_2$$

   $0.3\ M \times V_1 = 0.15\ M \times 100\ mL \qquad V_1 = 50.0\ mL$

Mass of reagents needed to prepare 100 and 250 mL of buffer

Solution and Concentration	Amount Needed for 100 mL of Buffer (g)	Amount Needed for 250 mL of Buffer (g)
0.05 M sodium acetate ($NaC_2H_3O_2$)	0.410	
0.10 M sodium acetate	0.820	2.051
0.15 M sodium acetate	1.231	
0.05 M ammonium chloride (NH_4Cl)	0.268	
0.10 M ammonium chloride	0.535	1.337
0.15 M ammonium chloride	0.802	

Volume of solutions needed to prepare 100 and 250 mL of buffer

Final Concentration	0.3 M Acetic Acid or 0.3 M Ammonia	
	Volume Needed for 100 mL of Buffer (mL)	Volume Needed for 250 mL of Buffer (mL)
0.05 M	16.7	
0.10 M	33.3	83.25
0.15 M	50.0	

5. Obtain the appropriate size volumetric flask.

6. Fill the volumetric flask halfway with distilled water.

7. Obtain _____ grams of solid _____ and add it to the volumetric flask.

    NOTE: Do not *fill the flask with water.*

8. Use a graduated cylinder to measure _____ milliliters of _____ and add it to the volumetric flask. Swirl the flask to mix the solution.

9. Fill the volumetric flask to the mark with distilled water. Mix the solution thoroughly by inverting the flask several times.

10. Rinse a 50-mL beaker three times with distilled water.

11. Rinse the 50-mL beaker twice with small portions of your buffer solution.

12. Pour about 25 mL of your buffer solution into the 50-mL beaker and measure the pH of your solution. Record the pH in the Model 1 Data Table.

❷ 13. Why is it necessary to rinse the 50-mL beaker with distilled water, and then with the solution you want to test?

    Rinsing with water removes remnants of solutions previously in the beaker that may react with the buffer and alter the pH. Rinsing with the buffer solution will remove any remaining water so that the buffer solution is not diluted and the pH is accurate.

14. Label and save your remaining buffer for building Model 2. Share your pH data with your classmates to complete the Model 1 Data Table.

Model **1 – Buffer Preparation**

Table 1: Model 1 Data Table—pH of buffers of different volumes and concentrations

Solution Number	Molarity of Weak Base	pKa	Molarity of Conjugate Acid	Ratio of Weak Base to Conjugate [BOH] / [B+]	Total Volume of Buffer Solution	pH of Buffer Solution	|pK$_a$– pH|
1	0.05 M NH$_3$	9.25	0.05 M NH$_4^+$	1:1	100 mL	9.52	0.27
2	0.10 M NH$_3$	9.25	0.10 M NH$_4^+$	1:1	100 mL	9.56	0.31
3	0.10 M NH$_3$	9.25	0.10 M NH$_4^+$	1:1	250 mL	9.56	0.31
4	0.15 M NH3	9.25	0.15 M NH$_4^+$	1:1	100 mL	9.88	0.63
5	0.15 M NH$_3$	9.25	0.05 M NH$_4^+$	3:1	100 mL	10.44	1.19
6	0.05 M NH$_3$	9.25	0.15 M NH$_4^+$	1:3	100 mL	9.20	0.05

Solution Number	Molarity of Weak Acid	pKa	Molarity of Conjugate Base	Ratio of Weak Acid to Conjugate [HA] / [A⁻]	Total Volume of Buffer Solution	pH of Buffer Solution	|pK$_a$– pH|
7	0.05 M CH$_3$COOH	4.74	0.05 M CH$_3$COO⁻	1:1	100 mL	4.48	0.26
8	0.10 M CH$_3$COOH	4.74	0.10 M CH$_3$COO⁻	1:1	100 mL	4.25	0.49
9	0.10 M CH$_3$COOH	4.74	0.10 M CH$_3$COO⁻	1:1	250 mL	4.25	0.49
10	0.15 M CH$_3$COOH	4.74	0.15 M CH$_3$COO⁻	1:1	100 mL	4.59	0.15
11	0.15 M CH$_3$COOH	4.74	0.05 M CH$_3$COO⁻	3:1	100 mL	3.46	1.28
12	0.05 M CH$_3$COOH	4.74	0.15 M CH$_3$COO⁻	1:3	100 mL	5.17	0.43

Analyzing Model 1 – Buffer Preparation

15. Use a reference source to look up the K_a and determine the pK_a of the weak acid or conjugate acid involved in each of the solutions in the Model 1 Data Table.

    Refer to the pK_a column in the Model 1 Data Table.

    Sample calculation for Solution 7, K_a = 1.8 × 10⁻⁵ :

    pK_a = –log K_a

    pK_a = –log (1.8 × 10⁻⁵)

    pK_a = 4.74

16. Calculate the weak acid or weak base to conjugate ratio for each buffer solution in Model 1.

    Refer to the Model 1 Data Table.

    For example, for Solution 1, the molarity of each solution is 0.05 M. Therefore, the [BOH]/[B⁺] ratio is 1:1.

    a. Which ratios of weak acid or weak base to the conjugate solution have the pH of the buffer the closest to the pK_a?

    Ideally, students should find that the pKa is closest to the pH when the ratio is 1:1.

17. Compare the buffers having the same molarity of components, but with different total volumes. Does the volume of the buffer system prepared affect the pH of the resulting solution? Provide specific examples from Model 1 to support your answer.

    No, the volume prepared does not affect the pH. Refer to the sample data for buffers 2 and 3 and buffers 8 and 9. In both cases, the pH of the sample data is the same.

18. How would you respond to a person who mistakenly said "Buffers are made so that the solution remains neutral"? Provide specific examples from Model 1 to support your answer.

None of the buffer solutions had a pH of 7. Buffers are made so the pH change due to adding acid or base is minimized.

19. Suppose you wanted to make a buffer solution that would keep the pH near 3. Which of the following mixtures would suffice?

    Solution A   0.10 M lactic acid and 0.10 M sodium lactate

    Solution B   0.10 M hypochlorous acid 0.10 M sodium hypochlorite

    Solution C   0.10 M benzoic acid and 0.10 M sodium benzoate

Students will need to look up the pK_a for each solution.

Lactic acid: pK_a = 3.86

Hypochlorous acid: pK_a = 7.46

Benzoic acid: pK_a = 4.19

Solution A with lactic acid and sodium lactate would be the best choice; its pK_a is closest to the desired pH.

MODEL 2

Building Model 2 – Buffer Capacity

1. Rinse three test tubes several times with distilled water. Assign one pipet for the deionized water, one for the buffer, and one for the universal indicator.

2. Place 10 drops of deionized water in a test tube. Add one drop of universal indicator to the water and note the initial color. Add 0.10 M HCl solution drop-wise, mixing between drops, until the solution changes to red-orange (pH ≤ 3). In Model 2, record the number of drops of HCl solution added to make this color change occur.

3. Place 10 drops of your buffer solution in a test tube. Add one drop of universal indicator to the solution and note the initial color. Add 0.10 M HCl solution drop-wise, mixing between drops, until the solution changes to red-orange (pH ≤ 3). Record the number of drops of HCl solution added to make this color change occur.

    NOTE: If your solution contains CH_3COOH and CH_3COO^-, then don't carry out this step.

4. Place 10 drops of deionized water in a test tube. Add one drop of universal indicator to the water, and note the initial color. Add 0.10 M NaOH solution drop-wise, mixing between drops, until the solution changes to purple (pH ≥ 11). Record the number of drops of NaOH solution added to make this color change occur.

5. Place 10 drops of your buffer solution in a test tube. Add one drop of universal indicator to the solution, and note the initial color. Add 0.10 M NaOH solution drop-wise, mixing between drops, until the solution changes to purple (pH ≥ 11). Record the number of drops of NaOH solution added to make this color change occur.

    NOTE: If your solution contains NH_4^+ and NH_3, then don't carry out this step.

6. Share your data with your classmates to complete the Model 2 Data Table.

Model 2 – Buffer Capacity

Drops of HCl needed in distilled water to turn the color red-orange: _____1_____

Drops of NaOH needed in distilled water to turn the color purple: _____1_____

Table 2: Model 2 Data Table—Comparing buffer capacity

Solution Number	Molarity of Weak Base	Molarity of Conjugate Acid	Total Volume of Buffer Solution	Drops of HCl Needed	Drops of NaOH Needed
1	0.05 M NH_3	0.05 M NH_4^+	100 mL	3	
2	0.10 M NH_3	0.10 M NH_4^+	100 mL	8	
3	0.10 M NH_3	0.10 M NH_4^+	250 mL	8	
4	0.15 M NH_3	0.15 M NH_4^+	100 mL	9	
5	0.15 M NH_3	0.05 M NH_4^+	100 mL	11	
6	0.05 M NH_3	0.15 M NH_4^+	100 mL	3	
Solution Number	Molarity of Weak Acid	Molarity of Conjugate Base	Total Volume of Buffer Solution	Drops of HCl Needed	Drops of NaOH Needed
7	0.05 M CH_3COOH	0.05 M CH_3COO^-	100 mL		6
8	0.10 M CH_3COOH	0.10 M CH_3COO^-	100 mL		9
9	0.10 M CH_3COOH	0.10 M CH_3COO^-	250 mL		9
10	0.15 M CH_3COOH	0.15 M CH_3COO^-	100 mL		14
11	0.15 M CH_3COOH	0.05 M CH_3COO^-	100 mL		13
12	0.05 M CH_3COOH	0.15 M CH_3COO^-	100 mL		11

Analyzing Model 2 – Buffer Capacity

The *buffer capacity* of a solution is related to the number of moles of acid and base that the solution can neutralize without a significant change in pH.

For each set of solutions shown below, consider the similarities and differences in their components. Refer to both the Model 1 Data Table and the Model 2 Data Table.

7. Compare the buffer volume, molarity, and pH:

   a. What is the molarity ratio of weak base to conjugate acid in solutions 2 and 3?

      1:1

   b. Was there a change in pH between solutions 2 and 3?

      No. The pH was the same. Creating more of the buffer with the same component molarities didn't affect the pH.

   c. What is the molarity ratio of weak acid to conjugate base in solutions 8 and 9?

      1:1

   d. Was there a change in pH between solutions 8 and 9?

      There was no change. Creating more of the buffer with the same component molarities didn't affect the pH.

   e. For solutions 2 and 3, and solutions 8 and 9, was there a difference in the number of drops of HCl or NaOH needed to obtain pH 1 or pH 14?

      Students should see little difference, if any, in the number of drops needed.

f. Considering the previous questions, what can be concluded about changing the volume of the buffer system without changing the ratio of weak acid to conjugate base, or weak base to conjugate acid, and its effect on pH?

Changing the volume of the buffer system without changing the ratio of acid or base to conjugate base or conjugate acid will not affect pH.

8. The following questions compare the number of moles of each buffer system component and the buffer capacity in solutions of equal volume:

a. What is the ratio of the number of moles of weak base between solutions 1 and 2 and between solutions 1 and 4?

The ratio of the number of moles of weak base between solutions 1 and 2 is 1:2. The ratio of the number of moles of weak base between solutions 1 and 3 is 1:3.

b. Was there a change in pH between solutions 1, 2 and 4?

In the sample data, there was no significant change. Students should see very little, if any, change between the two solutions.

c. What is the ratio of the number of moles of weak acid between solutions 7 and 8 and between 7 and 10?

The ratio of the number of moles of weak base between solutions 1 and 2 is 1:2. The ratio of the number of moles of weak base between solutions 1 and 3 is 1:3.

d. Was there a change in pH between solutions 7, 8, and 10?

In the sample data, there was a small change. Students should see very little, if any, change between the two solutions.

e. For solutions 1, 2, and 4, and solutions 7, 8, and 10, was there a difference in the number of drops of HCl or NaOH needed to obtain pH 1 or pH 14?

In both cases, as the concentration of the solutions increased, and therefore the number of moles in a sample of equal volume increased, more drops of HCl or NaOH were required to obtain pH 1 or pH 14.

f. Considering the previous questions, what can be concluded about buffer capacity and concentration? Give evidence from your data to support your answer.

The buffering capacity of buffer systems increases as the concentration of its buffer components increases, as shown in solutions 1, 2, and 4 and solutions 7, 8, and 10.

9. Do buffer systems stop the pH from changing? Give evidence from your data to support your answer.

Buffer systems resist a pH change, but don't stop the pH from changing. However, students should find that a greater number of drops of HCl or NaOH was needed to change the pH to pH 1 or pH 14 in the buffers, respectively, compared to when these solutions were added to water.

10. Do buffers with greater concentrations have greater buffer capacity? Give evidence from your data to support your answer.

Yes, the buffering capacity of buffer systems increases as the concentration of its buffer components increases, as shown in the increasing number of drops of HCl or NaOH in solutions 1, 2, and 4 and solutions 7, 8, and 10.

11. If you wanted to make a buffer of pH 9.5 with a buffer capacity greater than that in Solution 1 of Model 2, what would have to change in the buffer system?

To create a buffer with greater capacity, the concentration of the weak base and conjugate acid solutions should be greater than 0.1 M.

Connecting to Theory

Buffers are made from a weak acid or base and their respective conjugate. Two nutritional labels are shown below. One is from Monster Energy® drink and the other is from Mountain Dew®. By inspecting each label, you should be able to identify an acid and its conjugate. Together these form a buffer solution.

Remember, when acids are made from polyatomic acids, their ending is changed to "ic." The polyatomic ion of the conjugate will have an "ate" ending.

<table>
<tr>
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Nutrition Facts
Monster MW2 Assault Energy Drink
Serving Size - 8 fl. oz.
Servings per container - 2

Amount Per Serving
Calories - 100
Total Carb - 25g
Sugars - 25g
Vitamin B2 - 1.7mg
Vitamin B3 - 20mg
Vitamin B6 - 2mg
Vitamin B12 - 6mcg
Sodium - 1000mg
Taurine - 1000mg
Panax Ginseng - 200mg
Energy Blend - 2500mg

Ingredients: Carbonated Water, Sucrose, Glucose, Citric Acid, Sodium Citrate, Taurine, Natural Flavors, Panax Ginseng Root Extract, Phosphoric Acid, L-Caratine, Caffeine, Sorbic Acid, Benzoic Acid, Caramel Color, Niacinamide, Sucralose, Sodium Chloride, Glucuronolactone, Inositol, Gurana Seed Extract, Certified Color, Pyrodozine Hydrochloride, Riboflaven, Maltodextrin, Cyanocobalamin

Consume Responsibly - Limit 3 cans per day. Not recommended for children, pregnant women, or people sensitive to caffeine.

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<td>

Nutrition Facts
Halo 3 Mountain Dew Game Fuel
Serving Size - 1 Can

Amount Per Serving
Calories - 170
Total Carb - 0g
Sodium - 65mg
Total Carbohydrates - 46g
Sugars - 46g
Protein - 0g

Caffeine Content: 73mg/12 fl. oz.

Ingredients: Carbonated Water, High Fructose Corn Syrup, Citric Acid, Natural Flavors, Sodium Benzoate, Gum Arabic, Caffeine, Sodium Citrate, Yellow 5, Gylcerol Ester of Wood Rosin, Cacium Disodium Edta, Yellow 6, Red 40, Brominated Vegetable Oil

Halo 3 Mountain Dew Game Fuel is not a significant source of other nutrients.

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Applying Your Knowledge – Making Your Own Buffer System

Listed below are solutions that can be combined to make buffers. Your teacher will assign you a pH. Your job will be to make 100 mL of a buffer solution with that pH, using these components.

After your teacher measures the initial pH, you will divide your solution between two beakers.

Your teacher will add 5 drops of 6.0 M HCl to one beaker and measure the pH to determine if it has changed. Five drops of 6.0 M NaOH will be added to the other beaker and similar measurements will be made.

Your first task is to find all of the conjugate relationships in the list below. Show each relationship and the information needed to calculate the pH for each. You need to be ready to prepare the solution that matches the assigned pH.

0.3 M Ammonium chloride (NH_4Cl)	0.3 M Potassium phosphate (K_3PO_4)
0.3 M Sodium acetate ($NaCH_3COO$)	0.3 M Sodium phosphate monobasic (NaH_2PO_4)
0.3 M Sodium phosphate dibasic (Na_2HPO_4)	0.3 M Acetic acid (CH_3COOH)
0.3 M Phosphoric acid (H_3PO_4)	0.3 M Ammonia (NH_3)

Guidelines for preparing the buffer solutions

pH to Assign	Conjugate Relationship	Weak Acid or Weak Base	Conjugate Base or Conjugate Acid	K_a	pK_a	Volume of Acid (mL)	Volume of Conjugate Base (mL)
2.15	$H_3PO_4 \rightleftharpoons H_2PO_4^-$	H_3PO_4	NaH_2PO_4	7.1×10^{-3}	2.15	50	50
4.74	$CH_3COOH \rightleftharpoons CH_3COO^-$	CH_3COOH	$NaCH_3COO$	1.8×10^{-5}	4.74	50	50
7.20	$H_2PO_4^- \rightleftharpoons HPO_4^{-2}$	NaH_2PO_4	Na_2HPO_4	6.3×10^{-8}	7.20	50	50
9.25	$NH_4^+ \rightleftharpoons NH_3$	NH_4Cl	NH_3	5.6×10^{-10}	9.25	50	50
12.38	$HPO_4^{-2} \rightleftharpoons PO_4^{-3}$	NaH_2PO_4	K_3PO_4	4.2×10^{-13}	12.38	50	50

NOTE: Use the following table to record the pH of the buffers.

Student results

Group	Assigned pH	Conjugate Relationship	Initial pH	pH after HCl	pH after NaOH
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					

Teacher Tips

Tip 1 – Have students perform both buffer labs

This manual has two labs that address the concept of buffers: Introduction to Buffers and Buffer Properties. The focus of Buffer Properties, buffer capacity, is the culmination of the Introduction to Buffers activity, so students will benefit if the two labs are carried out as if they were two parts of the same lab.

Tip 2 – Limitations of adding both NaOH and HCl to the buffers of Model 2

Students who have prepared the ammonia–ammonium chloride buffer should test the buffer capacity with only HCl, and those who have prepared the acetic acid–sodium acetate buffer should test the buffer capacity with only NaOH, as the indicator color is already close to that of pH 1 or pH 14 and students will have a difficult time detecting the change.

Tip 3 – Results not consistent with the theoretical expectation

Students should find, in Model 1, that the pH is closest to the pKa for the buffers with a 1:1 ratio. If they do not, due to the variability of this procedure, emphasize that the 1:1 ratio is the theoretical value that meets this condition and they should use that relationship when determining the solution makeup in the Applying Your Knowledge section.

17. MOVING ELECTRONS

Initial Question

Reactions that occur without outside intervention are said to occur spontaneously. Non-spontaneous reactions can occur if some outside factor provides enough energy. Electrolysis is the process of using electricity to force a non-spontaneous reaction to occur. Electrolysis can be used to separate pure metals from their ore and plate metals onto surfaces.

How can you make a non-spontaneous reaction do useful things?

Learning Objectives[*]

By electrolyzing a variety of aqueous solutions, students determine a relationship between current, electric charge, and quantity of electrons.

LO 3.12 / The student can make qualitative or quantitative predictions about galvanic or electrolytic reactions based on half-cell reactions and potentials and/or Faraday's laws.

LO 3.13 / The student can analyze data regarding galvanic or electrolytic cells to identify the properties of the underlying redox reactions.

SP4.1 / The student can *justify the selection of the kind of data* needed to answer a particular scientific question.

SP 6.1 / The student can *justify claims with evidence*.

Time Requirement

Preparation time: 30 minutes / Lab activity: 180 minutes (two 90-minute class periods)

Materials and Equipment

All Models
- Data collection system
- Voltage–current sensor
- Wire leads, 2 red, 1 black
- Electrodes (2)
- Alligator clips (4), 2 red, 2 black

- 9 V Battery
- 9 V Battery cap with leads
- Beaker, glass, 400-mL
- Stirring rod
- Wash bottle with distilled water

Model 1
- Test tubes (2), 10 mm × 75-mm
- Universal indicator, 20 drops
- Scoopula™ spatula

- Epsom salt (Magnesium sulfate, $MgSO_4$), 4–6 marble-size scoops
- Distilled water, 600 mL

Model 2
- Potassium iodide, KI, 1 marble-size scoop
- Scoopula™ spatula

- Copper(II) bromide, ($CuBr_2$), 1 marble-size scoop
- Distilled water, 600 mL

Model 3

- Copper strip
- Steel wool
- Metals strip, spoon, or key

- 1.0 M Copper(II) sulfate ($CuSO_4$), 100 mL[1]
- Analytical balance, 1 per class

[1] To prepare 1.0 M Copper(II) sulfate from copper sulfate pentahydrate ($CuSO_4 \cdot 5H_2O$) refer to the Lab Preparation section.

Applying Your Knowledge

- Copper strip
- Steel wool
- Metal strip, spoon, or key

- 1.0 M Copper(II) sulfate, ($CuSO_4$), 100 mL[1]
- Analytical balance, 1 per class

[1] To prepare 1.0 M Copper(II) sulfate from copper sulfate pentahydrate ($CuSO_4 \cdot 5H_2O$) refer to the Lab Preparation section.

Prerequisites

Students should be familiar with the following concepts:

- Stoichiometry of chemical reactions

- Molarity

- Acid and base solutions

- Electrolytes

- Conductivity

- Oxidation and reduction half-cell reactions

- Reduction potential

- Voltage

- Current

Lab Preparation

These are the materials and equipment to set up prior to the lab:

Model 3 and Applying Your Knowledge

1.0 M Copper(II) sulfate pentahydrate: To prepare 1 L of 1.0 M copper(II) sulfate pentahydrate ($CuSO_4 \cdot 5H_2O$), fill a 1000-mL volumetric flask 1/3 full of distilled water. Add 249.68 g of copper(II) sulfate pentahydrate to the flask and swirl to dissolve. Fill the flask to the mark with distilled water.

Model 3

NOTE: In Model 3, the reaction will be carried out for a period of time between 5 and 15 minutes. Assign student groups a different period of time for electroplating an object, starting at 5 minutes and ending at 15 minutes, so that the groups have a time for every other minute, that is, 5, 7, 9, 11, 13, and 15 minutes. Students will share the data for the time periods they haven't done.
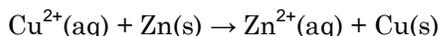
Safety

Add these important safety precautions to your normal laboratory procedures:

- Potassium iodide and copper(II) bromide solutions may cause skin irritation. If you come in contact with either of them, flush the area with plenty of water.
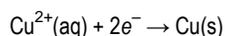
Getting Your Brain in Gear

1. The following reaction is a spontaneous oxidation–reduction reaction:

$$Cu^{2+}(aq) + Zn(s) \rightarrow Zn^{2+}(aq) + Cu(s)$$

   a. What is the oxidation half-cell reaction?

   $Zn(s) \rightarrow Zn^{2+}(aq) + 2e^-$
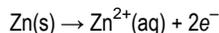
   b. What is the reduction half-cell reaction?

   $Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$

   c. Using a standard reduction potential table, what is the overall standard cell potential for this reaction?

$Zn(s) \rightarrow Zn^{2+}(aq) + 2e^-$	E^o = +0.76 V
$Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$	E^o = +0.34 V
	E^o = +1.10 V

   d. How can we say that this reaction is spontaneous?

   The overall cell potential is positive, indicating a spontaneous reaction.

2. What is the oxidation number for sulfur in sulfate (SO_4^{+2})?

   The oxidation number is +10.

3. When you use universal indicator, what ion is present if the solution is in the range of orange to red? What ion is present if the solution is in the range of blue to purple? What does a blue-green solution color indicate?

   Hydrogen ions are present; they make the solution acidic, indicated by the red–orange color. Hydroxide ions are present; they make the solution basic. A blue-green solution has a neutral pH.

4. Like water moving in a stream, the movement of electrons through a circuit is called a *current*. Which of these ionic solutions would have a current? Justify your answer.

A   B
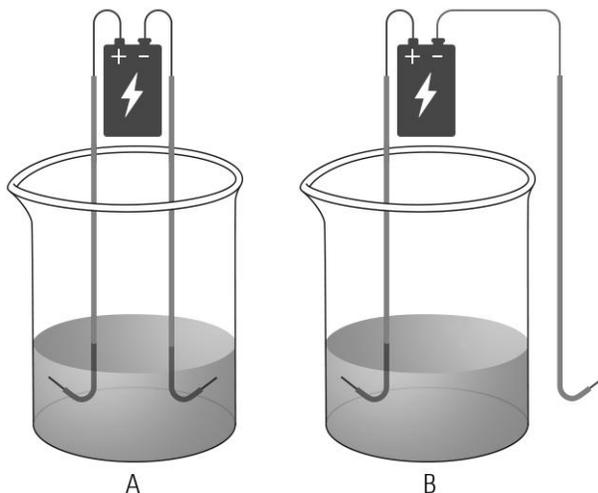
Beaker A could have a current because the circuit is complete through the liquid. Only a closed circuit will carry a current.

MODEL 1

Building Model 1 – Electrolysis of Water

1. Connect the voltage–current sensor to the data collection system.

2. Set up the electrodes, 9 V battery, and voltage-current sensor as shown in the circuit diagram. Place the alligator clips over the banana plugs when needed to connect to wires or electrodes.

   NOTE: You will use this setup for the rest of the lab.

3. Create a graph of current versus time.

4. Add approximately 300 mL of deionized water to a 400-mL beaker (fill it to the 300-mL line). Place the electrodes into the water and start collecting data.

5. Record the current in the Model 1 Data Table.

6. Add 2–3 marble-size scoops of Epsom salt ($MgSO_4$) to the distilled water.

7. Stir the mixture to dissolve the Epsom salt. Be careful not to hit the electrodes.

8. Record the current and your observations in the Model 1 Data Table.

9. Stop data collection.

10. Disconnect the circuit from the battery and obtain a fresh sample, 300 mL, of deionized water. Rinse the electrodes and place them back in the beaker.

11. With the battery still disconnected, add 2–3 scoops of the Epsom salt and 10 drops of universal indicator. The indicator will turn blue to purple in basic solutions and orange to red in acidic solutions.

12. Stir the solution. Once all of the Epsom salt has dissolved, record the color of the solution in the Model 1 Data Table.

13. Completely fill two test tubes with the Epsom salt solution. Cover the test tubes with your fingers to hold the solution in. Invert them into the beaker so the solution does not spill. Remove your fingers once the test tubes are inverted in the solution.
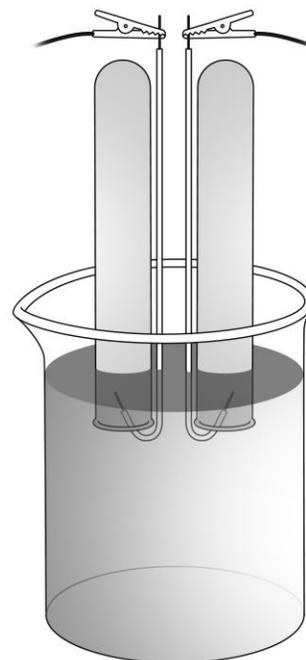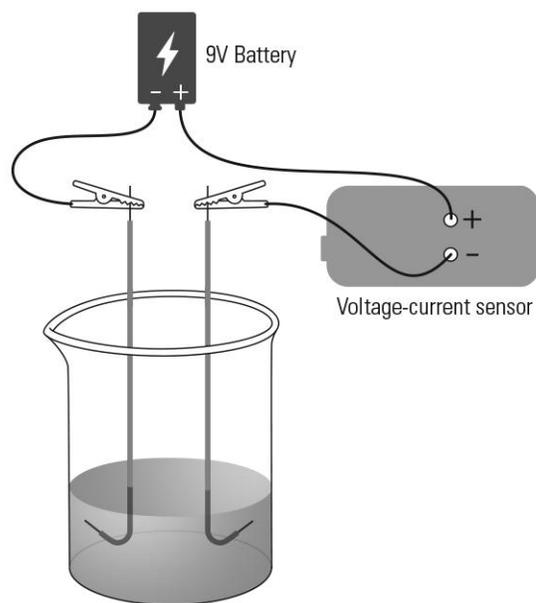
    NOTE: Magnesium sulfate (Epsom salt) is non-toxic (it is often added to bath water).

14. Insert the electrodes into the openings of the inverted test tubes.

15. Start data collection and reconnect the battery.

16. Record the current and your observations in the Model 1 Data Table.

17. After 2 minutes, stop data collection and disconnect the battery.

Model 1 – Electrolysis of Water

Table 1: Model 1 Data Table—Determine the half-reactions

Solution	Current (A)	Observations
Deionized water	0.00	No reaction
Deionized water + magnesium sulfate	0.05	Bubbles at both electrodes
Deionized water + magnesium sulfate + universal indicator, *before* battery is connected		Blue-green solution
Deionized water + magnesium sulfate + universal indicator, *after* battery is connected	0.05	Purple (basic) at the cathode, with bubbles Red (acidic) at the anode, with bubbles

Analyzing Model 1 – Electrolysis of Water

18. Why does the current change when the magnesium sulfate is added to water?

Distilled water is not a good conductor. Magnesium sulfate ions in solution make the solution conductive.

❓ 19. Draw a particulate-level representation of the Epsom salt solution. Predict which way the ions flow.
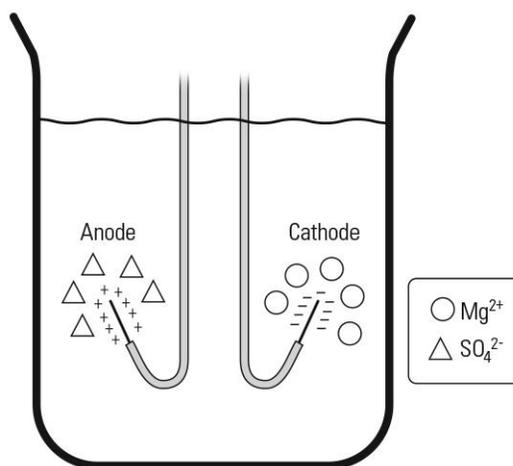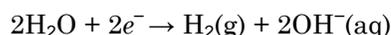

The positive magnesium ions will be attracted to the negative electrode and the negative sulfate ion will be attracted to the positive electrode.

20. The cathode of the electrolytic cell was attached to the negative end of the battery. At the cathode, reduction occurred. In this cell, the reaction could be

$$Mg^{2+}(aq) + 2e^- \rightarrow Mg(s)$$

OR
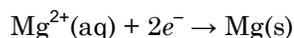
$$2H_2O + 2e^- \rightarrow H_2(g) + 2OH^-(aq)$$

Based on your observations, which reaction occurred? Justify your answer.

The reaction that occurred was $2H_2O + 2e^- \rightarrow H_2(g) + 2OH^-(aq)$.

The solution around the cathode (the electrode connected to the negative end of the battery) turned purple, indicating that a base had formed. Bubbles were produced at this electrode, indicating a gas had been produced. Hydrogen gas is a product of this reaction.

21. The anode of the electrolytic cell is attached to the positive end of the battery (through the voltage–current sensor). Based on your observations, what is one of the products of this oxidation? Explain.

The solution turned red, which means that it had become acidic, so H$^+$ ions must have been produced.

22. The sulfur in sulfate is already in a very high oxidation state so it is safe to assume that the water, not sulfur, is being oxidized at the anode. What is the balanced half-cell reaction equation for the reaction occurring at the anode?

$2H_2O \rightarrow 4e^- + 4H^+(aq) + O_2(g)$

23. Based on the oxidation and reduction half-reactions, what is the overall balanced equation for the electrolysis?

$2H_2O \rightarrow O_2(g) + 2H_2(g)$. Refer to the Teacher Tip: Balancing Basic Half-Reaction

MODEL 2

Building Model 2 – Electrolysis of Potassium Iodide and Copper(II) Bromide

Electrolysis of Potassium Iodide

1. Connect the voltage–current sensor to the data collection system.

2. Set up the electrodes, the 9 V battery, and current sensor as in Model 1.

3. Create a graph of current versus time.

4. Obtain a fresh 300-mL sample of deionized water. Rinse the electrodes and place them back in the beaker.

5. With the battery still disconnected, add one marble-size scoop of potassium iodide. Stir the solution, taking care not to hit the electrodes.

6. After the potassium iodide has dissolved, start data collection and connect the battery.

7. Record the current and your observations in the Model 2 Data Table.

8. After about 30 seconds, stop data collection and disconnect the battery.

Electrolysis of Copper(II) Bromide

9. Obtain a fresh 300-mL sample of deionized water. Rinse the electrodes and place them back in the beaker.

10. With the battery still disconnected, add a marble-size scoop of copper(II) bromide. Stir the solution, taking care not to hit the electrodes.

11. Start data collection and reconnect the battery.

12. Record the current and your observations in the Model 2 Data Table.

13. After 30 seconds, stop data collection and disconnect the battery.

Model 2 – Electrolysis of Potassium Iodide and Copper(II) Bromide

Table 2: Model 2 Data Table—Anode and cathode activity

Solution	Current (A)	Observations
Deionized water with potassium iodide	0.05	Bubbles formed at the cathode and brownish liquid appeared at the anode.
Deionized water with copper(II) bromide	0.05	Brown-black solid deposits formed on the anode and the solution around the cathode turned a slight yellow-brownish color.

Analyzing Model 2 – Electrolysis of Potassium Iodide and Copper(II) Bromide

14. When the electrodes were placed in the KI solution, there were two possible reduction reactions that could occur at the cathode:
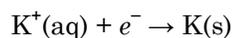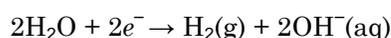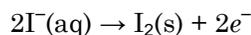
$$K^+(aq) + e^- \rightarrow K(s)$$

OR

$$2H_2O + 2e^- \rightarrow H_2(g) + 2OH^-(aq)$$

Which reaction occurred? Justify your answer.

The reaction that occurred was $2H_2O + 2e^- \rightarrow H_2$ (g)+ $2OH^-$ (aq).

Bubbles were produced at the cathode, indicating hydrogen gas had been created. There was no solid produced, which would have indicated the first reaction shown had occurred.

15. When the electrodes were placed in the KI solution, there were two possible oxidation reactions that could occur at the anode:

$$2I^-(aq) \rightarrow I_2(s) + 2e^-$$

OR

$$2H_2O \rightarrow O_2(g) + 4e^- + 4H^+(aq)$$
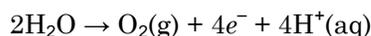
Which reaction occurred? Justify your answer.

The reaction that occurred was $2I^-$ (aq) $\rightarrow I_2(s) + 2e^-$.

Since brownish-black solid was produced and no bubbles formed, then the first reaction, where iodine was formed, occurred.

16. Draw a particulate-level representation of the potassium iodide solution immediately after the current started and then after 30 seconds later. Add the charge on each electrode.

Current at t=0   After 30 seconds of current
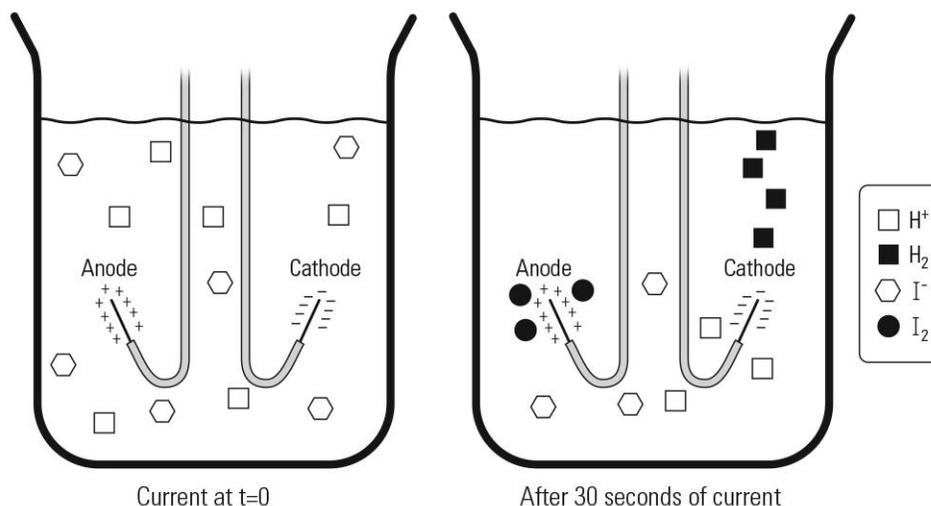
17. Based on your observation, how is the half-reaction cell voltage related to the reaction that occurs experimentally?

Table 3: Potentials for KI and H_2O half-reactions

Half-Reaction	E^o
$K^+(aq) + e^- \rightarrow K(s)$	−2.93 V
$2H_2O + 2e^- \rightarrow H_2(g) + 2OH^-(aq)$	−0.83 V
$2I^-(aq) \rightarrow I_2(s) + 2e^-$	−0.53 V
$2H_2O \rightarrow O_2(g) + 4e^- + 4H^+(aq)$	−1.23 V

The reaction with the least negative cell potential (or greatest positive cell potential) will occur.

18. The aqueous solution in Model 1 contains magnesium sulfate. Magnesium ions and sulfate ions have the following reduction and oxidation reactions and potentials:

$$Mg^{2+}(aq) + 2e^- \rightarrow Mg(s) \qquad\qquad E^o = -1.18 \text{ V}$$

$$2SO_4^{2-}(aq) \rightarrow S_2O_8^{2-}(aq) + 2e^- \qquad\qquad E^o = -2.05 \text{ V}$$
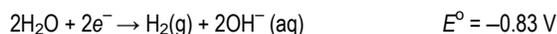
Why did neither of these half-reactions occur when the magnesium sulfate solution was electrolyzed?

These reactions did not occur because both of these half-reactions have a greater negative potential than the reduction and oxidation of water.

19. What are the two possible reduction reactions and their half-cell potentials that could occur when the electrodes are placed in the copper(II) bromide solution?

Either of the following could occur:

$Cu^{+2}(aq) + 2e^- \rightarrow Cu(s)$ $\qquad\qquad E^o = 0.34 \text{ V}$

$2H_2O + 2e^- \rightarrow H_2(g) + 2OH^-(aq)$ $\qquad\qquad E^o = -0.83 \text{ V}$

20. Which reduction reaction occurred when a solution of copper(II) bromide was electrolyzed? Give a theoretical and an experimental justification for your answer.

$Cu^{+2}(aq) + 2e^- \rightarrow Cu(s)$
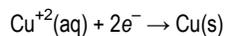
This half-reaction has a more positive theoretical value and solid copper formed at the cathode (experimental).

21. What are the two possible oxidation reactions that could occur when the electrodes are placed in the copper(II) bromide solution?

Either of the following could occur:

$2Br^-(aq) \rightarrow Br_2(l) + 2e^-$ $\qquad\qquad E^o = -1.07 \text{ V}$

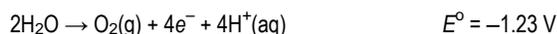$2H_2O \rightarrow O_2(g) + 4e^- + 4H^+(aq)$ $\qquad\qquad E^o = -1.23 \text{ V}$

22. Which oxidation process occurred when a solution of copper(II) bromide was electrolyzed? Give a theoretical and an experimental justification for your answer.
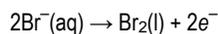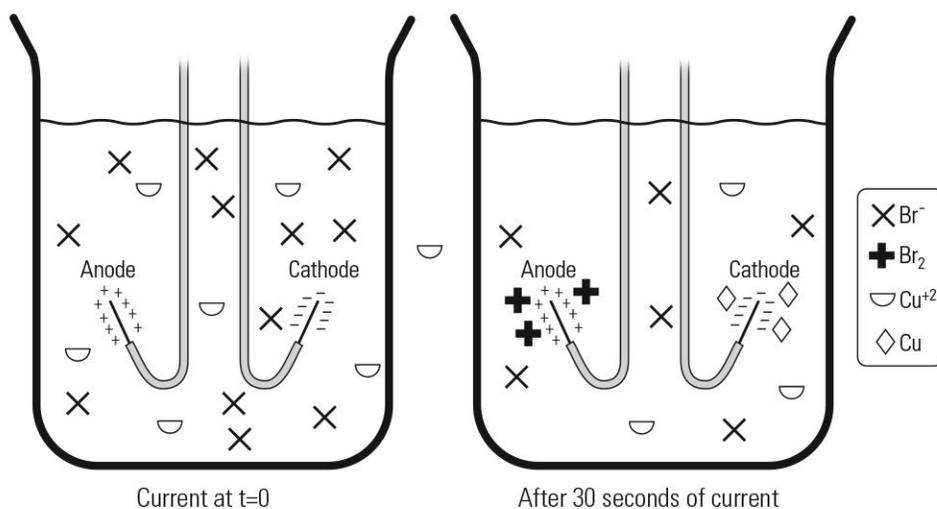
$2Br^-(aq) \rightarrow Br_2(l) + 2e^-$

This half-reaction has a more positive theoretical value and liquid bromine appeared at the anode (experimental).

23. Draw a particulate-level representation of the copper(II) bromide solution immediately after the current started and then 30 seconds later. Add the charge on each electrode.

Current at t=0   After 30 seconds of current

MODEL 3

Building Model 3 – Charge and Number of Electrons

1. Your teacher will assign each group an amount of time to carry out the reaction.

2. Connect the voltage–current sensor to the data collection system.

3. Set up the electrodes, 9 V battery, and voltage–current sensor as in Model 1, except use a spoon or metal strip as one of the electrodes and a clean, shiny copper strip as the other. Do not let the spoon come in contact with the other electrode; it will cause a short circuit.

4. Clean the copper strip with steel wool if necessary and rinse it with distilled water. Leave the copper strip out of the solution until you are ready to start data collection. Dry the copper strip and measure its mass. Record the mass in the Model 3 Data Table next to the reaction time assigned to your group.

5. Create a graph of current versus time.

6. Rinse the beaker and obtain 100 mL of 1.0 M copper(II) sulfate (fill the beaker to the 100-mL line).

7. When the battery is connected, there are two possible reduction reactions that could occur at the cathode in the copper(II) sulfate solution:

$$Cu^{+2}(aq) + 2e^- \rightarrow Cu(s) \qquad\qquad E^o = 0.34 \text{ V} \qquad OR$$
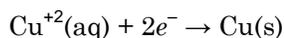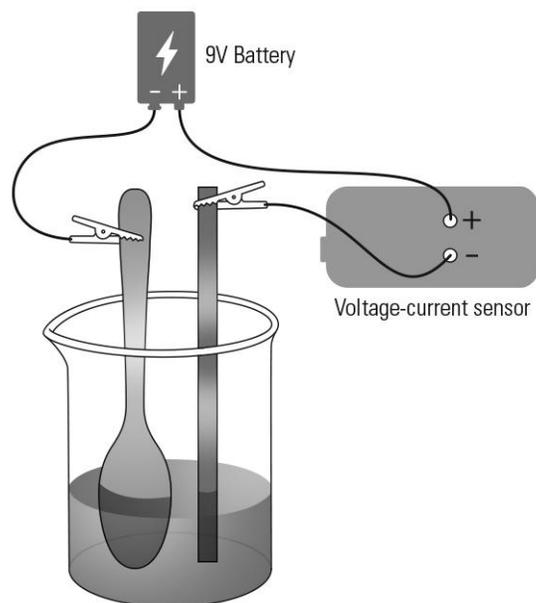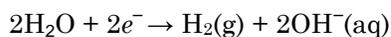
$$2H_2O + 2e^- \rightarrow H_2(g) + 2OH^-(aq) \qquad\qquad E^o = -0.83 \text{ V}$$

Which reaction will occur and why?

Cu^{+2}(aq) + 2e$^-$ → Cu(s) will occur. This reaction has a more positive potential.

8. When the battery is connected, there are two possible reduction reactions that could occur at the anode in the copper(II) sulfate solution:

$$Cu(s) \rightarrow Cu^{+2}(aq) + 2e^- \qquad\qquad E^o = -0.34 \text{ V} \qquad OR$$
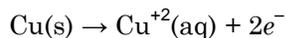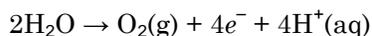
$$2H_2O \rightarrow O_2(g) + 4e^- + 4H^+(aq) \qquad\qquad E^o = -1.23 \text{ V}$$

Which reaction will occur and why?

Cu(s) → Cu^{+2}(aq) + 2e$^-$ will occur. This reaction has a more positive potential.

9. Based on the half-reactions that occur at the anode and cathode, what physical observations could you make during this reaction? Is the copper strip the anode or the cathode?

The copper strip will lose copper and the solid copper will be deposited onto the spoon. The copper strip is the anode.

10. Start data collection and connect the battery.

11. Record the current in the Model 3 Data Table.

12. After the assigned time has elapsed, disconnect the battery and stop data collection.

13. Carefully remove the strip of copper and the spoon.

14. Dry the copper strip. Record the mass of the copper strip in the Model 3 Data Table.

15. Share your measurements with your classmates to complete the columns of initial and final mass of the copper strip in the Model 3 Data Table.

Model 3 – Charge and Amount in Moles

Table 4: Model 3 Data Table— Aqueous to solid

Reaction Time (min)	Current (A)	Initial Mass of Copper Strip (g)	Final Mass of Copper Strip (g)	Change in Mass of Copper (g)	Number of Moles of Copper Reacted (mol)	Number of Moles of Electrons (mol)	Charge (C)	Ratio: Charge/ Number of Moles of Electrons (C/mol e^-)
5	0.44	4.1749	4.1336	0.0413	6.50×10^{-4}	1.30×10^{-3}	132.00	102000
7	0.37	4.1228	4.0733	0.0495	7.79×10^{-4}	1.56×10^{-3}	155.40	100000
9	0.48	4.0656	3.9878	0.0778	1.22×10^{-3}	2.44×10^{-3}	259.20	106000
11	0.30	3.9689	3.9056	0.0633	9.96×10^{-4}	1.99×10^{-3}	198.00	100000
13	0.42	1.7479	1.6445	0.1034	1.63×10^{-3}	3.26×10^{-3}	327.60	100000
15	0.50	1.8311	1.6849	0.1462	2.30×10^{-3}	4.60×10^{-3}	450.00	97800
Average ratio of charge to the number of moles of electrons:							101000	

Analyzing Model 3 – Charge and Amount in Moles

16. Calculate the change in mass of the copper or each reaction time. Record these values in the Model 3 Data Table.

    For the 5-minute trial: 4.1749 g – 4.1336 g = 0.0413 g

17. For each reaction time, use the change in mass of copper of the copper strip to calculate the number of moles of copper that reacted and record the results in the Model 3 Data Table.

    For the 5-minute trial: $\dfrac{0.0413 \text{ g Cu}}{1} \times \dfrac{1 \text{ mole Cu}}{63.546 \text{ g Cu}} = 6.50 \times 10^{-4}$ mole Cu

18. Use the half-reaction and the number of moles of copper lost by the copper strip to calculate the number of moles of e^- that reacted. Record the results in the Model 3 Data Table.

    Half-reaction: $Cu(s) \rightarrow Cu^{+2}(aq) + 2e^-$

    For the 5-minute trial: $\dfrac{6.5 \times 10^{-4} \text{ mole Cu}}{1} \times \dfrac{2 \text{ mole } e^-}{1 \text{ mole Cu}^{2+}} = 1.3 \times 10^{-3}$ mole e^-

19. By plotting current (A) versus time (s), and using the equation $q = It$, where q is the charge measured in coulombs (abbreviated as "C"), the current I is measured in amperes (abbreviated as "A"), and time t is measured in seconds, you can determine the charge required—the charge is the area under the curve. Calculate the charge and record it in the Model 3 Data Table.

    Current versus Time
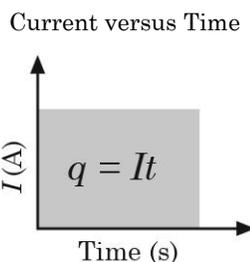
    For the 5-minute trial: $q = It$; $q = 0.44 \text{ A} \times 300 \text{ s} = 132$ coulombs

    Students can also obtain the charge using the equipment to find the area under the curve.

20. What happens to the change in mass of copper as the charge increases?

    The change in the mass of copper increases when the charge increases.

21. Calculate the ratio of charge to the number of moles of electrons for all of the reaction times and record it the Model 3 Data Table.

For the 5-minute trial: $\dfrac{132 \ \text{coulomb}}{1.30 \times 10^{-3} \ \text{mole } e^-} = 101000 \dfrac{\text{coulomb}}{\text{mole } e^-}$

22. What is the average ratio of the charge to moles of electrons for your data?

For the sample data, the average ratio is 101000.

23. Is the ratio of charge to moles of electrons consistent for all the groups?

Yes, the ratio for all of the groups is consistent. In the sample data, the greatest difference is 6000/101000.

Connecting to Theory

Michael Faraday was one of the greatest experimental scientists. He was self-taught and felt uncomfortable with his math abilities so would rely on other scientists for help. Faraday has influenced modern chemistry, environmentalism, and physics. For nineteen years he would show off his discoveries during Christmas Lectures, which were designed to inspire young scientists. His Christmas Lectures became a tradition and continue to this day at the Royal Institution in London.

In Model 3, you calculated the ratio of charge to the number of moles of electrons. This ratio is known as Faraday's constant. A Faraday F is equal to 96,485 coulombs per mole of electrons. It is usually expressed as

$$F = \frac{96{,}485 \ \text{coulumbs}}{1 \ \text{mole } e^-}$$

Applying Your Knowledge – Plating Copper on a Spoon

Electroplating is the process of coating an electrically conductive object with a layer of metal using an electric current. The process, also known as electrodeposition, is used to improve the appearance and increase hardness and corrosion resistance of the plated objects.

After calculating the length of time it will take to plate 0.1 g of copper onto a spoon, create an electroplating cell from $CuSO_4$ solution using a key or spoon, and a copper strip, using the same setup as in the earlier models.

1. Calculate the average current for Model 3.

Model 3 average current

Time (min)	Current (A)	Average Current (A)
5	0.44	
7	0.37	
9	0.48	0.42
11	0.30	
13	0.42	
15	0.50	

For the sample data: (0.44 A + 0.37 A + 0.48 A + 0.30 A + 0.42 A + 0.50 A) /6 = 0.42 A

2. Using the average current and Faraday's constant, determine how long it will take to plate 0.1 g of copper onto a spoon.

Based on the sample data and using the ratio of electrons to copper, $Cu^{2+} + 2e^- \rightarrow Cu(s)$

:

$$\frac{0.1 \text{ g Cu}}{1} \times \frac{1 \text{ mol Cu}}{63.546 \text{ g Cu}} \times \frac{2 \text{ mol } e^-}{1 \text{ mol Cu}} \times \frac{96,485 \text{ C}}{1 \text{ mol } e^-} = 303.67 \text{ C}$$

$q = It$ so $t = \dfrac{q}{I}$

$$\frac{303.67 \text{ C}}{0.42 \text{ A}} = 732.02 \text{ s}; \quad \frac{732.02 \text{ s}}{60 \text{ s/min}} = 12.05 \text{ min}$$

3. Perform the experiment to plate 0.1 g of copper onto a spoon and determine the actual yield of copper.

    Copper yield: _____0.720_____ g

Determine the mass of copper deposited

Initial Mass of the Spoon (g)	Final Mass of the Spoon (g)	Change in Mass of the Spoon (g)
41.1127	41.1855	0.0720

4. What is the percent error of your yield?

$$\text{Percent Error} = \frac{\left|\text{Theoretical Value} - \text{Experimental Value}\right|}{\text{Theoretical Value}} \times 100$$

For the sample data:

$$\frac{\left|0.1 \text{ g} - 0.0720 \text{ g}\right|}{0.1 \text{ g}} \times 100 = \frac{0.028 \text{ g}}{0.1 \text{ g}} \times 100 = 28\% \text{ error}$$

5. What factors may have caused the deviation from your theoretical and your actual yield?

    Sources of error could be due to lower voltage from battery than the calculated average, poor connections, electrodes touching, or incorrect calculation of the time.

Teacher Tips

Tip 1 – Balancing Basic Half-Reactions

Balancing basic half-reactions is often problematic for students. The following method accounts for neutralization of the hydrogen ion with the hydroxide ion when the reaction occurs.

anode $\quad 2H_2O \quad\quad\quad \rightarrow \quad 4e^- \quad + 4H^+(aq) \quad + O_2(g)$
cathode $\quad 2H_2O \quad + 2e^- \quad \rightarrow \quad\quad\quad + H_2(g) \quad\quad + 2OH^-(aq)$

It is performed by adding enough hydrogen ions to neutralize the hydroxide ions in the basic half-reaction. In this example, a reaction resulting in a basic product occurs at the cathode. Add the hydrogen ions to both sides of the equation to maintain balance.

$$2H_2O \quad + 2e^- \quad \rightarrow \quad H_2(g) \quad + 2OH^-(aq)$$
$$+2H^+ \quad\quad\quad\quad\quad\quad\quad\quad\quad +2H^+$$

The hydrogen and hydroxide ions combine to form water.

$$2H^+ \quad +2H_2O \quad + 2e^- \quad \rightarrow \quad H_2(g) \quad + 2H_2O$$

Water is now on both sides of the equation and cancel out.

$$2H^+ \quad + 2e^- \quad \rightarrow \quad H_2(g)$$

The reaction at the anode and cathode can now be combined to form the overall equation:

anode $\quad 2H_2O \quad\quad\quad \rightarrow \quad 4e^- \quad + 4H^+(aq) \quad + O_2(g)$
cathode $\quad 2H^+ \quad + 2e^- \quad \rightarrow \quad H_2(g)$

The reaction at the cathode is multiplied by two to balance the electrons.

anode $\quad 2H_2O \quad\quad\quad \rightarrow \quad 4e^- \quad + 4H^+(aq) \quad + O_2(g)$
cathode $\quad 4H^+ \quad + 4e^- \quad \rightarrow \quad 2H_2(g)$

The hydrogen ions and electrons cancel out.

anode $\quad 2H_2O \quad\quad\quad \rightarrow \quad\quad\quad\quad\quad + O_2(g)$
cathode $\quad\quad\quad\quad\quad\quad \rightarrow \quad 2H_2(g)$

The reaction at the cathode and anode are combined to form the overall balanced equation.

overall balanced $\quad 2H_2O \quad \rightarrow \quad 2H_2(g) \quad + O_2(g)$
equation

APPENDIX A: SENSOR CALIBRATION

Calibrating a drop counter

The drop counter is calibrated as follows, using the SPARK Science Learning System® or SPARKvue® software calibration procedure to correlate the number of drops counted to the volume of liquid dispensed from the drop dispenser.

Materials and Equipment

- Data collection system
- Drop counter
- Drop dispenser:
  Syringe, 60-mL
  Stopcock (2)
  Drop tip

- Graduated cylinder, 10-mL
- Beaker, for waste
- Multi clamp
- Ring stand
- Three-finger clamp
- Titrant

Calibration

1. Attach the drop dispenser (syringe, two stopcocks and drop tip) and drop counter to a support rod as shown.

2. Fill the syringe with titrant.

3. Place a beaker for waste under the drop dispenser.

4. Open both stopcock valves and adjust the valve on the top stopcock so that the drops fall at a rate of about 1 drop per second. Close the bottom valve after the rate is achieved. The top valve controls the flow rate and the bottom valve turns the flow on and off.

5. Using the multi clamp, attach the drop counter and connect it to the data collection system.

6. Align the drop tip with the opening in the drop counter. Remove the waste beaker and put a 10-mL graduated cylinder under the drop counter opening.

7. While on the **Home** screen, open the bottom stopcock to allow titrant to flow.

8. After almost 10 mL of titrant are collected in the graduated cylinder, close the stopcock.
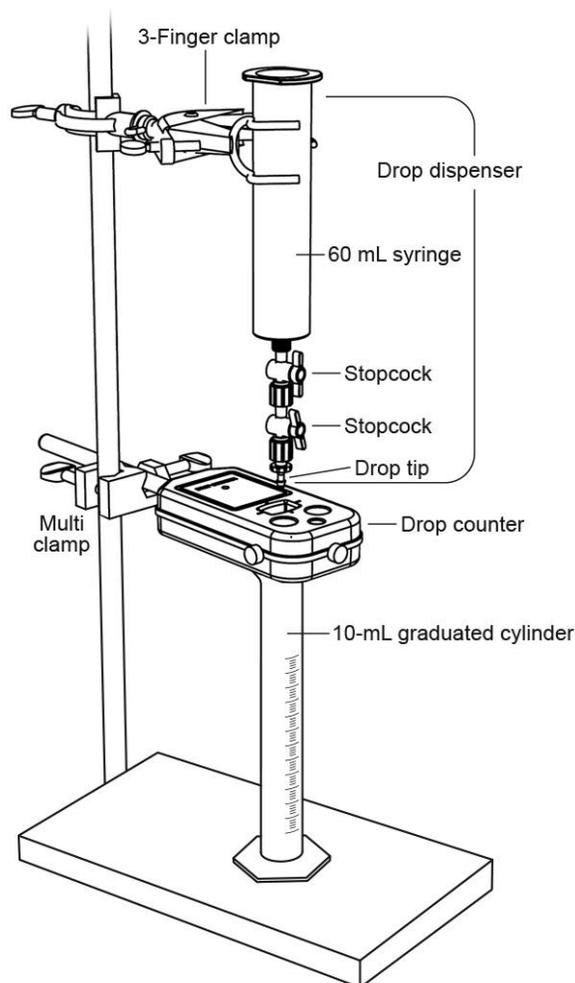
9. Record the exact volume of titrant in the graduated cylinder and the **Drop Count** from the **Home** screen**.**

10. Build the desired display for your experiment.

11. Select the **Experiment Tools** button.

    Result: The **Experiment Tools** screen opens.

12 Select **Calibrate Sensor**.

    Result: The **Calibrate Sensor: Select Measurement** screen opens.

13. Select the **Sensor** box and select **Drop Counter**.

14. Select the **Measurement** box and select **Fluid Volume (mL)**.

15. Select the **Calibration Type** box and select **1 point (Adjust Slope Only)**.

16. Select **NEXT**.

    Result: The **Calibrate Sensor** screen opens

17. Under **Calibration Point 2** select the **Standard Value** box and enter the recorded volume (10 mL).

18. Under **Calibration Point 2** select **Read From Sensor** to automatically input the number of drops the sensor counted that corresponds to that volume.

19. Select **OK** to exit the **Calibrate Sensor** screen.

20. Select **OK** to exit the **Experiment Tools** screen.

This QR code is a link to a YouTube video that shows the viewer how to calibrate a drop counter.

Calibrating a pH sensor

Materials and Equipment

- Data collection system
- pH sensor
- Buffers, pH 4 and pH 10

Calibration

1. Attach the pH sensor to the data collection system.

2. Press the **Home** button: .

3. Select **pH**.

4. Select **Show**. (You will see a graph display.)

5. Press the **Experiment Tools** button: .

6. Select **Calibrate Sensor**.

7. In the **Sensor** field, select the sensor that has the pH sensor attached.

8. In the **Measurement** field select **pH**.

9. **Calibration Type** should remain **2 point (Adjust Slope and Offset)**.

10. Select **NEXT**.

11. Enter the pH of the first buffer in the **Standard Value** box in the **Calibration Point 1** section.

12. Rinse and wipe dry the pH sensor.

13. Place the pH sensor in the buffer solution corresponding to the value in the **Standard Value** box.

14. Stir the buffer solution with the pH sensor for at least two seconds.

15. Select the **Read From Sensor** button.

16. Enter the pH of the second buffer in the **Standard Value** box in the **Calibration Point 2** section.

17. Rinse and wipe dry the pH sensor.

18. Place the pH sensor in the second pH buffer solution.

19. Stir the buffer solution with the pH sensor for at least two seconds.

20. Select the **Read From Sensor** button. The sensor is now calibrated.

21. Select **OK** twice to return to the graph display.