PROFESSIONAL DEVELOPMENT

AP® Chemistry

Guided Inquiry Activities for the Classroom

CURRICULUM MODULE

For the redesigned course launching Fall 2013

The College Board
New York, NY

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The College Board strongly encourages educators to make equitable access a guiding principle for their AP programs by giving all willing and academically prepared students the opportunity to participate in AP. We encourage the elimination of barriers that restrict access to AP for students from ethnic, racial and socioeconomic groups that have been traditionally underserved. Schools should make every effort to ensure their AP classes reflect the diversity of their student population. The College Board also believes that all students should have access to academically challenging course work before they enroll in AP classes, which can prepare them for AP success. It is only through a commitment to equitable preparation and access that true equity and excellence can be achieved.

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Preface

AP® curriculum modules are exemplary instructional units composed of one or more lessons, all of which are focused on a particular curricular topic; each lesson is composed of one or more instructional activities. Topics for curriculum modules are identified because they address one or both of the following needs:

- a weaker area of student performance as evidenced by AP Exam subscores
- curricular topics that present specific instructional or learning challenges

The components in a curriculum module should embody and describe or illustrate the plan/teach/assess/reflect/adjust paradigm:

1. *Plan* the lesson based on educational standards or objectives and considering typical student misconceptions about the topic or deficits in prior knowledge.
2. *Teach* the lesson, which requires active teacher and student engagement in the instructional activities.
3. *Assess* the lesson, using a method of formative assessment.
4. *Reflect* on the effect of the lesson on the desired student knowledge, skills, or abilities.
5. *Adjust* the lesson as necessary to better address the desired student knowledge, skills, or abilities.

Curriculum modules will provide AP teachers with the following tools to effectively engage students in the selected topic:

- enrichment of content knowledge regarding the topic;
- pedagogical content knowledge that corresponds to the topic;
- identification of prerequisite knowledge or skills for the topic;
- explicit connections to AP learning objectives (found in the AP curriculum framework or the course description);
- cohesive example lessons, including instructional activities, student worksheets or handouts, and/or formative assessments;
- guidance to address student misconceptions about the topic; and
- examples of student work and reflections on their performance.

The lessons in each module are intended to serve as instructional models, providing a framework that AP teachers can then apply to their own instructional planning.

Note on Web resources

All links to online resources were verified before publication. In cases where links are no longer working, we suggest that you try to find the resource by doing a key-word Web search.

— The College Board

Introduction

Marian DeWane, co-editor
University of California–Irvine
Irvine, Calif.

Tom Greenbowe, co-editor
Iowa State University
Ames, Iowa

In the 2013–2014 academic year, AP Chemistry will begin placing emphasis on guided-inquiry teaching and learning. The College Board provides definitions of different types of inquiry in “Inquiry Instruction in the AP Science Classroom: An Approach to Teaching and Learning” (http://media.collegeboard.com/digitalServices/pdf/ap/AP-Inquiry-Statement_Final_4-21-11.pdf). This curriculum module will introduce the concepts of guided inquiry, and its lessons will focus on some ways to use guided inquiry in the classroom. Mike Abraham and John Gelder have written a brief introduction to guided-inquiry theory; this background knowledge is essential to understanding guided-inquiry lessons and can be used to help you construct your own lessons grounded in inquiry. In Lesson 1, Renée Cole illustrates how to include a learning cycle in an instructional activity on representing chemical equations to help students understand concepts in stoichiometry; such a learning cycle is a vital component of guided inquiry. Lesson 2, written by Marian DeWane and Tom Greenbowe, utilizes the foundations of guided inquiry to structure a lesson using a computer simulation on acid-base neutralization reactions. The last lesson, by Laura Trout, addresses Valence Shell Electron Pair Repulsion (VSEPR) theory and takes you through a step-by-step approach to creating instructional activities that include guided inquiry.

Connections to the AP Chemistry Curriculum

To address the curriculum requirement of incorporating the science practices (SP), this curriculum module illustrates a variety of ways to implement the practices through guided inquiry. These include using models and representations (SP1), using mathematics (SP2), questioning (SP3), planning and collecting data (SP4), analyzing data (SP5), supporting claims with evidence (SP6), and including cross-curricular connections (SP7).

Connections to the AP Chemistry Exam

All questions on the AP Chemistry Exam will be directly tied to the course learning objectives and science practices. There is an emphasis on analyzing data, showing conceptual understanding of the learning objectives, and problem-solving skills. The lessons in this curriculum module will help students analyze data and develop a conceptual understanding of stoichiometry, acid-base neutralization reactions, and the Valence Shell Electron Pair Repulsion (VSEPR) model.

Instructional Time and Strategies

Within each lesson, a guided-inquiry activity transitions students to a deeper understanding of the essential questions. These activities include step-by-step instructions for you to follow. Although the lessons are on separate topics, it is suggested that they be carried out in the sequence provided. Some supplemental instruction may be necessary, depending on the needs of a particular class.

- **Lesson 1: Representing Chemical Equations and Stoichiometry**
  This lesson should be implemented at the beginning of the stoichiometry unit when balancing equations are introduced. Requires one 55-minute class period.

- **Lesson 2: Acid-Base Neutralization Reactions**
  This lesson should be implemented at the beginning of the solution stoichiometry and acid-base neutralization unit. Requires one 55-minute class period.

- **Lesson 3: Valence Shell Electron Pair Repulsion (VSEPR) Model**
  This lesson should be performed at the beginning of a unit pertaining to molecular shapes. Activity 1 requires about 20 minutes; Activity 2 requires about 50 minutes.

Guided Inquiry and the Learning-Cycle Approach

Michael Abraham
The University of Oklahoma
Norman, Okla.

John Gelder
Oklahoma State University
Stillwater, Okla.

What Is Inquiry Instruction?

The AP Chemistry curriculum requires you to incorporate inquiry into your instruction based on the science practices. To make this transition to inquiry, you will need an understanding of expectations for this type of instruction. Inquiry instruction is associated with several science practices, including the use of data to derive concepts, the use of questions to guide student learning, the involvement of students in instructional decisions, and emphasis on the use of evidence in inventing concepts. These characteristics of inquiry teaching have ramifications for how one interacts with students and the role of the instructional components in a curriculum unit.

Inquiry is only one strategy of instruction. It is designed primarily to help students develop an understanding of concepts and of scientific processes by invention and application. *Concepts* are theories or principles used to explain phenomena. *Processes* include interpreting data, using evidence in drawing conclusions, experimenting, and modeling (Livermore 1964). Students find it easier to remember factual information if facts are associated with a concept or principle.

Table 1 divides learning into different categories and lists the approaches research has shown to be effective with each category.

Table 1: Effective Instructional Tactics

Category of Learning	Definition	Example	Instructional Tactic
Concepts	Generalization, Principle, or Theory	Conservation of Mass	Inquiry Questioning
Processes	Method	Separation and Control of Variables	Practice
Skills (Laboratory, Mathematical)	Ability	Using a Balance Curve Fitting	Informing or Demonstrating
Facts	Observation Definition	Cu^{2+}(*aq*) is Blue Ag is Silver	Observing Informed in Context
Attitudes	Beliefs or Feelings	Chemistry Is Fun Curiosity About How Nature Works	Example

What Is the Learning Cycle?

A helpful way of characterizing instructional strategies used to teach concepts is to divide instructional activities into phases: *identification of the concept*, *demonstration of the concept*, and *application of the concept*. Inquiry-oriented strategies can be contrasted with other instructional strategies (including traditional approaches such as confirmational "cookbook" labs) by considering the following:

- the ways these phases are used in an instructional unit
- the sequence of their application
- the use of questions as a central instructional tactic
- the role experimental data (quantitative and qualitative) and other forms of information play in introducing conceptual ideas
- the emphasis on scientific processes
- student involvement in the decision process

The learning cycle is an example of an inquiry-oriented instructional strategy used to help students develop concepts. It can also be used to guide the construction or organization of units of instruction. First, students are exposed to data demonstrating the concept: the *Exploration Phase*. From that data the concepts may be derived, thus identified: the *Invention Phase*. Students may then apply the concept to other phenomena: the *Application Phase*. In contrast to many traditional instructional approaches, which simply tell students what they need to know, this inquiry-oriented approach is based upon interpreting student-collected data that can be used as evidence to make claims. Classroom discussions are focused on using data to *generate* or *invent* concepts, rather than *informing* students of the concepts. Textual materials are used to apply, reinforce, review, and extend concepts rather than introduce them. This approach encourages more active learning by students.

Table 2: Characteristics of the Learning-Cycle Approach

Phases of Instruction	Goal	Activities	Questions	Data
Explore	Explore relations and patterns in data	Laboratory, Demonstrations, Simulations, Video	What did you do? What did you observe?	Gathering Data and Information
Invent Concept	Develop and understand concepts with teachers/peers	Lecture/ Discussion	What does it mean?	Explaining Data and Information
Apply Concept	Apply, reinforce, review, extend, and understand concepts	Readings, Problem Sets, Application Questions, Verification Labs	Using what you know, answer the following...	Using Data and Information, Provide Evidence
Evaluate	Assess understanding	Examinations, Quizzes		

There are several characteristics that, when used in combination, establish the learning-cycle approach as a distinct instructional strategy. The Exploration Phase provides information, identified by the learning activity and used inductively by students during the Invention Phase. The key to this instructional approach is that the learner derives the concept from his or her observations of the behavior of a chemical system. In the Application Phase, learners use the invented concept to verify and modify their ideas through the deductive process. The learning-cycle approach takes into account both inquiry and exposition. It requires the learner to use both inductive and deductive logical processes.

Another important characteristic of an inquiry instructional approach is the central role played by questions. Although many teachers question their students, the types and depth of questions in inquiry are different. Questions directed to students during or right after an exploration activity might include: “What did you do?” and “What did you observe?” These questions are useful in a class discussion when you encourage students to reply using details along with in-depth explanations. The “What did you do?” question serves to orient students to the topic of the discussion. The “What did you observe?” question establishes consensus concerning what happened, allowing students to resolve differences and encouraging a focus on the data used to invent the target concept. During the concept Invention Phase, the question asked is “What does it mean?” This question allows students to discover a concept or have a concept invented for them by you. Finally, during the Application Phase, students can answer questions requiring the concept as prerequisite knowledge.

How to Construct a Lesson Incorporating a Learning Cycle

The steps are identifiable in the lessons provided. After identifying each, it will be easier to embark on trying this approach with your own materials.

1. Identify the concept/principle/law you are trying to teach (it is the target of the activity). This should be a big idea, not a skill or fact.
2. Write a concept statement. This can be in the form of a learning objective, or a learning objective can be the source of the concept in the first place as long as it is at the concept level.
3. Write a problem statement/question. This should be a descriptive statement or question, the answer for which is the concept. Be careful to not give the concept away. These statements can be used to introduce the activity to students.
4. Identify the data or observations that can be used to explore the concept. Write activities that will require students to collect appropriate data and/or make the observations that would lead to the concept.
5. Write questions or activities that will lead students to interpret the data or to draw a conclusion that will lead to the invention of the target concept.
6. Write questions or activities that will lead students to use or apply the concept in a new setting.

Lesson 1: Representing Chemical Equations and Stoichiometry

Renée Cole
University of Iowa
Iowa City, Iowa

Essential Questions

- How do you represent what occurs in a chemical reaction?
- What determines how much product can be produced in a chemical reaction? For example, given the balanced chemical equation $2A + B \rightarrow 3P$: if six atoms of "A" react with two atoms of "B," how many atoms of "P" can be made?

Lesson Summary

Stoichiometry is a fundamental concept in understanding the quantitative aspects of chemical reactions, but it is also a topic that both teachers and students sometimes find tedious and difficult. Stoichiometry deals with quantitative relationships between reactants, products, and a balanced chemical equation. A common approach to teaching stoichiometry is to simply teach a series of algorithms for doing calculations; while this approach may result in students being able to do calculations, it often results in student misconceptions. The lack of conceptual understanding of stoichiometry is also problematic when students work with acid-base titrations, gas laws, and equilibrium concepts. Students need a solid understanding of stoichiometry when working numerical problems involving amounts of reactants and products, symbolic representations, and particulate drawings. Using physical objects such as models, nuts and bolts, LEGO® pieces, or other manipulatives is an additional strategy to help students better understand what a chemical equation represents. This leads to a better understanding of stoichiometry.

Connections to the AP Chemistry Curriculum Framework

- Essential knowledge 1.A.3: Atoms and molecules interact with one another on the atomic level. Balanced chemical equations give the number of particles that react and the number of particles produced. Because of this, expressing the amount of a substance in terms of the number of particles, or moles of particles, is essential to understanding chemical processes.
- Essential knowledge 1.E.1: Physical and chemical processes can be depicted symbolically; when this is done, the illustration must conserve all atoms of all types.

  a. Various types of representations can be used to show that matter is conserved during chemical and physical processes.

     1. Symbolic representations
     2. Particulate drawings

- Essential knowledge 1.E.2: Conservation of atoms makes it possible to compute the masses of substances involved in physical and chemical processes. Chemical processes result in the formation of new substances, and the amount of these depends on the number and the types and masses of elements in the reactants, as well as the efficiency of the transformation.

  a. The coefficients in a balanced chemical equation represent the relative numbers of particles that are consumed and created when the process occurs.

- Enduring understanding 3.A: Chemical changes are represented by a balanced chemical equation that identifies the ratios with which reactants react and products form.
- Essential knowledge 3.A.1: A chemical change may be represented by a molecular, ionic, or net ionic equation.

  a. Chemical equations represent chemical changes and therefore must contain equal numbers of atoms of every element on each side to be "balanced."
  b. The balanced chemical equation for a reaction is capable of representing chemistry at any level, and thus it is important that it can be translated into a symbolic depiction at the particulate level, where much of the reasoning of chemistry occurs.

Student Learning Outcomes

As a result of this lesson, students should be able to:

- connect the number of particles, moles, mass, and volume of substances to one another, both qualitatively and quantitatively [LO 1.4, *see* SP 7.1].
- translate among macroscopic observations of change, chemical equations, and particle views [LO 3.1, *see* SP 1.5, 7.1].

Student Prerequisite Knowledge

This activity will be most effective if students are familiar with:

- particulate representations of matter
- the Law of Conservation of Matter
- the use of formulas to represent molecules and compounds

If students need reinforcement in these areas, have them practice drawing reactants and counting the number of each type of atom in the compounds and molecules present; then have students draw the products, count the number of each type of atom in the reactants, and compare it to the types and numbers of atoms in the product.

Common Student Misconceptions

There have been many research studies focused on identifying student misconceptions and their difficulty understanding concepts related to stoichiometry. Some of these include:

- Equating the mole ratio of molecules with the mass ratio of molecules in a reaction (Schmidt 1990)
- Understanding the role of the coefficient in a chemical-reaction equation and frequently including it in determining the molar mass of a substance (BouJaoude and Barakat 2000)
- Conserving atoms but not conserving molecules in a chemical reaction (Mitchell and Gunstone 1984)
- Understanding the concept of “limiting reagent” when one of the substances is added in excess (Huddle and Pillay 1996)
- Understanding the mole concept (Lazonby et al. 1982)

Many of these difficulties can be addressed using a guided-inquiry approach to teach stoichiometry concepts. Through the use of robust models and appropriately scaffolded questions, students will directly address these common conceptual challenges. Additionally, having students reflect on the appropriate relationships, rather than simply memorizing an algorithmic approach to arrive at a numerical answer, improves their conceptual understanding of both the qualitative and quantitative aspects of chemical reactions.

Teacher Learning Outcomes

Through this lesson, you should improve your skills in effectively implementing guided-inquiry activities. You should be able to create a plan for using guided inquiry in your course and identify strategies to facilitate particular activities in the classroom. In addition, the included student activity will help you guide students through exploring, developing, and applying concepts related to stoichiometry.

Teacher Prerequisite Knowledge

You must have a solid understanding of stoichiometry, including the Law of Conservation of Mass, balancing chemical equations, calculations of moles given the mass of a substance and the chemical formula, mole ratios, and molecular weight. You should be able to use simple shapes to represent atoms and molecules in particle-view diagrams and conserve atoms when doing initial and final particle views of a chemical reaction. You should be able to translate among “macroscopic observations of change,” chemical equations (symbolic representations), and particle-view representations. You need to be aware of common student misconceptions and common mathematical setup and calculation mistakes with stoichiometry.

Materials or Resources Needed

- Handout 1
- LEGOs, chemistry model kits, or toothpicks and gummy bears (optional)
- Small (2′ × 3′) whiteboards, one for each group (optional)

Activity: Facilitating Guided Inquiry in the Classroom: Chemical-Reaction Equations

Facilitating guided-inquiry activities and laboratories effectively has two basic phases. The first phase focuses on overall classroom structure and implementation; the second phase focuses on implementing activities in the classroom. Both phases are critical for guided-inquiry activities to achieve the desired learning outcomes for the class.

Phase One: Getting Ready for Guided-Inquiry Learning

The first step in planning to use guided inquiry in your class is to ask yourself a series of questions:

- *How often will I use guided-inquiry activities and laboratories?* The key to successfully engaging students in guided inquiry is to make sure it is a regular part of instruction. Guided-inquiry activities can be incorporated daily, weekly, or at the beginning of every major topic.
- *How will I structure the learning teams?* Guided-inquiry activities generally work most effectively if students are assigned to learning teams consisting of three to five students. This structure provides students with an opportunity to engage in collaborative discourse, which has been suggested as one way to support students’ conceptual understanding of science (Asterhan and Schwarz 2007; Osborne 2010; Zohar and Nemet 2002).

- *How will I assess group work?* Deciding how to assess the product of collective activity is more challenging than assessing individual student work. However, if groups are to function as a team and develop appropriate skills, there has to be some accountability for the team outcomes. Some options for assessment include collecting one completed activity per group; having groups complete a "recorder's report," where the group is responsible for recording answers to key concept questions and reflections on process skills; or having group members take turns assessing the group process. In addition, the High School Process Oriented Guided-Inquiry Learning (POGIL) Initiative (http://www.pogil.org/high-school/hspi) has developed materials to help students assess and improve their personal effectiveness in interacting in groups. Group quizzes are another mechanism for building group interdependence and fostering discussion of concepts. They can be particularly effective if students gain immediate feedback about the correctness of their answers (Epstein et al. 2002; Yelkur 2005).

LESSON 1: Representing Chemical Equations and Stoichiometry

Useful website

Phase Two: Activity Implementation

Step 1. Draw an atom-level view on the board, using a triangle to represent a nitrogen atom and a circle to represent an oxygen atom. Provide students with this key. Next, draw two connected circles and two triangles connected to three circles. Ask students what compound the diagram represents. The connected circles represent an oxygen molecule, O_2, and the triangle and circles represent nitrogen oxide (or dinitrogen trioxide), N_2O_3. Having students convert the pictures to molecular formulas helps them translate between particulate and symbolic representations. Ask students to use the aforementioned pictures to represent the following reaction: nitrogen gas reacts with oxygen gas to form dinitrogen trioxide gas. Have them focus on the changes that occur as they move through the sequence of pictures. Emphasize that chemical-reaction equations represent chemical changes occuring as a result of interactions—they do not just describe the contents of a container. The structure of having students develop the origin of the coefficients in the chemical-reaction equations should also help address the difficulties students sometimes have in understanding the role of the coefficient in a chemical-reaction equation. If needed for differentiation, you may go through this step again using physical models (e.g. LEGOs) this time.

Step 2. In order to orient students to the purpose of the activity in Handout 1, provide some context for understanding why knowing what balanced chemical equations represent is important. Introduce this activity by demonstrating a chemical reaction (e.g., a video clip of a small piece of magnesium ribbon or iron burning in air and then in a container of oxygen gas), and discuss the importance of being able to communicate what happens during chemical reactions. After the demonstration, provide each student with a copy of Handout 1 and direct them to form small groups. In each group, assign the role of facilitator, spokesperson, quality control, and process analyst. If necessary, provide students with laminated role cards (http://www.pogil.org/uploads/media_items/pogil-role-cards-high-school.original.pdf) to help them take responsibility for their assigned components of teamwork. Students should take about six minutes to

Handout 1

Useful website

complete questions 1–4, and the groups' answers to questions 1, 2a, 4a, and 4b should be written on their whiteboards or reported out verbally during a group discussion.

Questions 1–4 prompt students to demonstrate their prerequisite knowledge. Write the instructions on the board or project them to provide a reference for the task. It may be helpful to students if you post the time by which they should be prepared to report out. While students are working, walk around the classroom listening to the discussions and answering questions. Do not provide the answers to the guided-inquiry questions. Interactions with students should help them process the information and draw conclusions, rather than presenting them with information and then providing answers. The nature and quality of teacher interventions has a significant impact on student learning in a collaborative-learning environment (Chiu 2004).

Step 3. There are many strategies for managing the pace at which students complete an activity. You can use multiple-choice questions along with a polling strategy (e.g., student response systems, colored index cards, holding one to five fingers in front of their chest, etc.) to check for understanding; have students report out using whiteboards; or have groups report out verbally. If most of the groups need a little more time, have the facilitators indicate by show of fingers how many more minutes their group needs to finish the questions. It is important to let students know when they are expected to get to particular points in the activity and help them progress efficiently through it.

Step 4. When using inquiry-based instruction, it is critical that closure is provided at the end of the activity so that students have a chance to reflect on what they have learned. When students are actively engaged in working through concepts, it is sometimes difficult for them to recognize that they have learned the material; it is much easier to distinguish when you have been "taught" something when the material is presented to you. For this reason, if students leave an inquiry class without closure, they may focus on what they do not understand and their frustration in learning new material, rather than focusing on what they have accomplished. At the end of class, close with a very brief discussion of the essential knowledge and understandings addressed in the activity. If you will not finish the activity before the end of class, you should identify a stopping point and discuss the knowledge and understandings developed to that point. You can either assign the remaining questions as homework and have the groups briefly compare their answers to those questions during the following class period or have the groups complete the activity during the next class period.

Formative Assessment

After students have completed questions 1–4 of Handout 1, inspect their responses. If there are disagreements in answers, this provides an excellent opportunity for students to critique responses and develop critical-thinking skills. Have the groups present their rationales and let students discuss which is the better response. You may have to guide this discussion to help students consider the appropriate factors. If all the groups have correct answers, ask the spokespersons from randomly selected groups to provide the rationale for their answers; also solicit answers for questions 2b and 3. Be careful not to always have the groups with either the correct or wrong answer go first in presenting their rationale. Students need to understand this process is not evaluative; rather, it is an opportunity to address misconceptions or improper procedures as well as to identify common mistakes. Sometimes two answers may be correct but qualitatively different in their articulation of a concept or depth of understanding. This provides an opportunity to discuss scientific communication and argumentation and why one response is more complete than another.

Repeat the above procedure, having students work on questions 5–10. The whole-class discussion for these questions may also involve a short presentation on representing chemical-reaction equations and how to determine reactants and products, depending on student responses to the questions. After they report their responses, have students move on to questions 11–15. It is important for them to have correct answers to these questions before they move on to questions 16–18. Resist the temptation to correct students as they are working. Having students compare answers amongst themselves and describe the process that they used to determine the answers is a richer learning opportunity, and it promotes student proficiency in the science practice of justifying claims with evidence as well as selecting and justifying an appropriate mathematical routine. Finally, have students complete questions 16–18 and report their responses.

Reflection on Formative Assessment

Each reporting session will provide you with the opportunity to reflect on the formative assessment. If students have correct responses and are engaged in scientifically appropriate discourse, move on to the next set of questions. However, if there is evidence students have not developed the concepts, this should prompt a mini-lecture or teacher–student discourse following an elicit-respond-elaborate pattern. For example, in question 9, if students have reactants that are "left over" included in the products column, help them develop a better understanding of reactants and products by using real-life analogies, such as making sandwiches, or by using physical models.

Lesson 2: Acid-Base Neutralization Reactions

Thomas J. Greenbowe
Iowa State University
Ames, Iowa

Marian L. DeWane
University of California–Irvine
Irvine, Calif.

Essential Questions

- How do the balanced chemical equation, the volume of acid used, and the volume and concentration of base required to reach the equivalence point and to neutralize the acid affect the calculation of the concentration of the acid?
- How does the particle drawing of an acid and a base affect the particle drawing of the resultant solution?

Lesson Summary

Strong acids react with strong bases to produce a salt and water. For example, when an aqueous solution of hydrochloric acid reacts with an aqueous solution of sodium hydroxide in a 1-to-1 ratio of moles, the resultant solution differs from the original reactants. Given a known amount and concentration of acid, a known amount and concentration of base will neutralize the acid. The primary concept for students to understand is neutralization means the point where the initial number of moles of hydronium ions (H_3O^+) from the acid equals the number of moles of hydroxide ion (OH^-) added from the base. This is called the *equivalence point*. The balanced chemical equation provides information about the ratio of moles of acid to moles of base. Acid-base titration problems present opportunities to have students make connections between three levels of representation: macroscopic (acid-base titrations in the lab), symbolic (balanced chemical equations), and the particulate nature of matter (particulate drawings).

To differentiate instruction, some students might gain a better understanding by using a graphing approach, others may benefit from using molecular model kits and doing additional picture diagrams, while still others may benefit by solving additional end-of-chapter problems from the textbook. Students can increase their understanding of acid-base reactions by doing titrations with different acids and bases in the chemistry laboratory either before or after this activity. All students benefit by experiencing a variety of methods.

Connections to the AP Chemistry Curriculum Framework

In big idea 1 of the curriculum framework, students are expected to design and interpret data from an experiment to determine the concentration of an analyte. In order to accomplish this, they need to have mastered background knowledge from these other sections of the curriculum framework:

- Essential knowledge 1.A.3: Atoms and molecules interact with one another on the atomic level. Balanced chemical equations give the number of particles that react and the number of particles produced. Because of this, expressing the amount of a substance in terms of the number of particles, or moles of particles, is essential to understanding chemical processes.
- Essential knowledge 1.E.1: Physical and chemical processes can be depicted symbolically; when this is done, the illustration must conserve all atoms of all types.
- Essential knowledge 1.E.2: Conservation of atoms makes it possible to compute the masses of substances involved in physical and chemical processes. Chemical processes result in the formation of new substances, and the amount of these depends on the number and the types and masses of elements in the reactants, as well as the efficiency of the transformation.
- Enduring understanding 3.A: Chemical changes are represented by a balanced chemical equation that identifies the ratios with which reactants react and products form.

Student Learning Outcomes

As a result of this lesson, students should be able to:

- design and/or interpret data from an experiment that uses titration to determine the concentration of an analyte in a solution [LO 1.20, *see* SP 4.2, 5.1, 6.4].
- express the Law of Conservation of Mass quantitatively and qualitatively using symbolic representations and particulate drawings [LO 1.17, *see* SP 1.5].
- identify a given solution as containing a mixture of strong acids and/or bases and calculate or estimate the pH (and concentrations of all chemical species) in the resulting solution [LO 6.15, *see* SP 2.2, 2.3, 6.4].

- 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 [LO 3.4, *see* SP 2.2, 5.1, 6.4].
- apply conservation of atoms to the rearrangement of atoms in various processes [LO 1.18, *see* SP 1.4].
- translate among macroscopic observations of change, chemical equations, and particle views [LO 3.1, *see* SP 1.5, 7.1].

Student Prerequisite Knowledge

This activity will be most effective if students are familiar with:

- using stoichiometry (balancing chemical equations, calculating moles, and identifying limiting reagents)
- calculating molarity of solutions
- classifying acids and bases, naming common inorganic acids and identify strong and weak acids and bases
- acid-base titrations and acid-base indicators

Students who need a refresher on how acids and bases react may benefit by doing a short online simulation where they can add indicators, identify acids and bases, and see how acids and bases react (see http://www.wisc-online.com/Objects/ViewObject.aspx?ID=GCH6204).

Useful website

Common Student Misconceptions

- Thinking a neutral solution is formed when any acid reacts with a base.
- Thinking that increasing the number of hydrogen atoms within a molecule increases the acidity of the compound.
- Assuming it takes less base to neutralize a weak acid than is required to neutralize a strong acid, given the two acids have the same initial concentration.

The first misconception can be addressed by having students do simple titrations involving different acids and then measure the pH at neutralization; this should be followed by a discussion about the hydrolysis reaction of the salt formed. The other misconceptions can be addressed by testing the pH of weak and strong acids and bases while comparing the number of hydrogen atoms present in a Lewis structure and the amount needed to neutralize the acid, again followed by a discussion. On Handout 2, Activity 1 provides a way to help students gain a conceptual understanding of neutralization reactions of acids and bases.

Handout 2

Teacher Learning Outcomes

Through this lesson, you will improve your skills in effectively implementing guided-inquiry activities. You should be able to create a plan for using guided inquiry when presenting the topic of acid-base neutralization reactions and identify strategies to facilitate particular activities in the classroom. The included student activity will help you guide students through exploring, developing, and applying stoichiometry concepts related to acid-base neutralization reactions.

Teacher Prerequisite Knowledge

You must have a solid understanding of the main topics in stoichiometry, acid-base reactions, acid-base titrations, the role of acid-base indicators, Lewis diagrams of acids and bases, simple acids including carboxylic acids, simple bases including ammonia, acid-base equilibria systems, salts, and acid-base reaction particulate drawings commonly presented in a college-level general chemistry textbook.

Materials or Resources Needed

- Handout 2
- Computers and Internet access to the acid-base titration computer simulation (or the computer simulation, which can be downloaded prior to class)
- Calculator and graph paper

Activity: Acid-Base Reactions

Step 1. Have students write the Law of Conservation of Matter, and then ask them the following:

- If matter is neither created nor destroyed during a chemical reaction, what can you say about the atoms involved in a chemical reaction?
- How can you determine when all of the acid reacts with the base, at the atom level, given the following chemical reaction: $HClO_4(aq) + NaOH(aq) \rightarrow NaClO_4(aq) + H_2O(l)$?
- Draw a diagram representing a small portion of the initial system with 10 $HClO_4(aq)$ units: How many $NaOH(aq)$ units would be needed to react with all of the acid? Explain what you did and what it indicates.

Handout 2

Step 2. Distribute Handout 2, and direct students to complete Activities 1 and 2. Students will need to work in pairs to complete the computer simulation, which will provide them with a variety of acids and bases, as well as a variety of amounts and concentrations of the acids and bases, to conduct a series of titrations. You may assign students a specific acid and base to titrate so that at least four acids and four bases are titrated; this allows the class to investigate at least four different concentrations of acids and bases. Students should be able to work through Activities 1 and 2 in about 20 minutes.

Step 3. Direct students to complete Activity 3. This activity will require students to think about mole ratios in acid-base reactions, as well as developing particulate representations of such reactions.

Step 4. Direct students to complete Activities 4 and 5. Students will need to transfer the content and skills learned in the prior activities to new data and new lab situations.

Formative Assessment

As students are working on Activity 2 with their partners, move around the room and check for student understanding of acid-base stoichiometry. When students have finished the tasks, they should record their data on the board. Every pair should enter data, including type of acid, initial concentration of acid, volume of acid, moles of H_3O^+ ions, concentration of base, volume of base required, and moles of OH^- ions added. Students should create aligned graphs and draw diagrams at the atom level using the collected data on the board. Students should be able to see patterns in the data. If the paired students are not understanding the concept and not finding the correct calculations and graphs, ask guiding questions to help them focus on the stoichiometry and the target concept (e.g., the number of initial moles of hydronium ions should equal the number of moles of hydroxide ions added to neutralize the acid).

Reflection on Formative Assessment

Ask yourself, "Are students' calculations, graphs, and picture diagrams consistent with the gathered data?" If some students struggle with understanding the main idea of acid-base titrations on the handout or show calculations and graphs inconsistent with the data, you may need to do another lesson with them on balancing chemical equations, basic stoichiometry, and molarity calculations.

Lesson 3: Valence Shell Electron Pair Repulsion (VSEPR) Model

Laura Trout
Lancaster Country Day School
Lancaster, Pa.

Essential Questions

- What factors determine the three-dimensional shape of molecules?
- How does the shape of a molecule, along with intermolecular forces, affect its macroscopic properties?

Lesson Summary

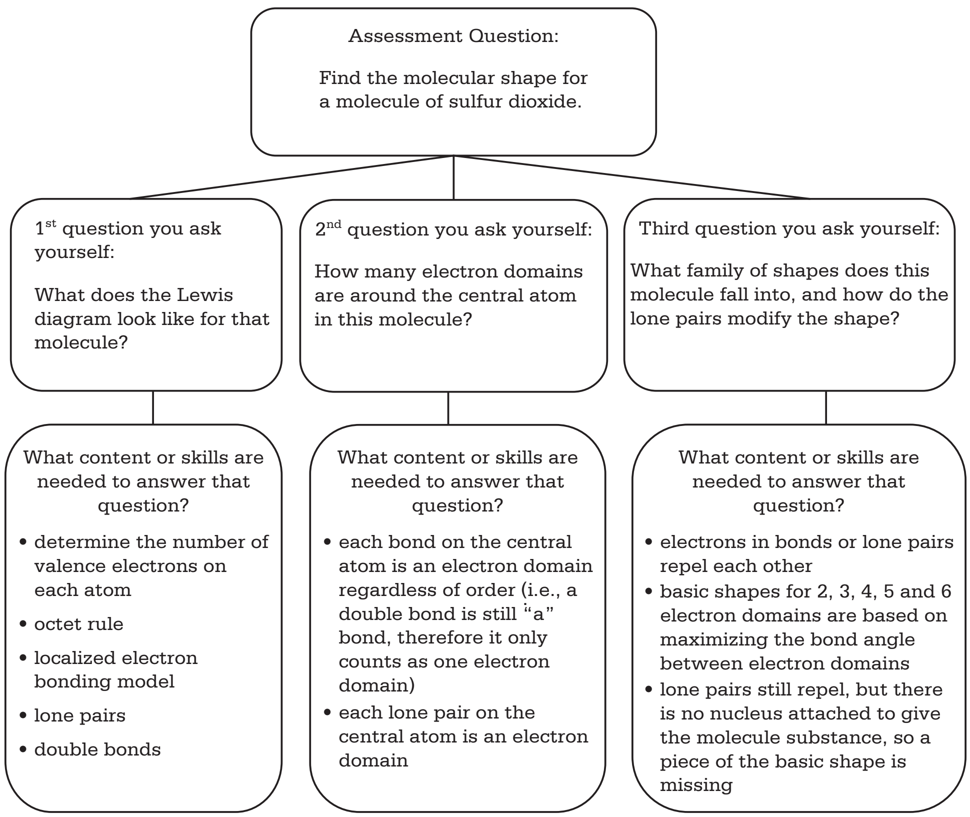
The VSEPR (Valence Shell Electron Pair Repulsion) model is a key topic in understanding physical properties of substances. Without an understanding of the factors governing molecular shapes, electronegativity, and chemical bonding, students cannot consistently predict the polarity of a substance, which is necessary for determining the types of intermolecular bonds present. Students need to understand the VSEPR model in order to facilitate the predicting or comparing of melting points, boiling points, phases, solubilities, and vapor pressures of substances.

In a typical lesson on the VSEPR model, students are told they can identify the shape of the molecule based on a Lewis diagram, and the idea that repulsion occurs between electron domains (bonds or lone pairs) is explained. The teacher may go into more detail by saying the bonds and lone pairs try to get as far from each other as possible in three-dimensional space; therefore, the bond angles are maximized. At this point in the lesson, there is often reference to shape names such as on Handout 4, with references to the number of bonds and number of lone pairs in the molecule, perhaps even with the shapes organized into "families" that have the same total number of electron domains around the central atom. The teacher may or may not have models of each shape, and he or she would probably work through a few examples for students before sending them off to work on exercises, a worksheet, or possibly to build some of their own molecular models to determine the molecular shape.

Handout 4

In a guided-inquiry class, however, we hope students use their understanding of electron repulsion to *discover* the basic shapes around a central atom in a molecule. To construct a lesson in this manner, it is useful to use a backward design model. This requires you to think about how to approach developing a molecular shape and bond-angle exercise. What questions do you ask yourself as you work through the problem? What skills or content knowledge is necessary for you to answer those questions? Finally, of those skills or content-knowledge pieces, which should be prerequisites for this lesson? In other words, where do you start? For example, suppose you were asked to find the molecular shape for sulfur dioxide (SO_2). The following graphic organizer shows how a teacher might think through that problem to plan a lesson backward.

Figure 1: Analysis of an assessment question for backward design of a lesson



As you look at the analysis of the assessment question in Figure 1, note that it starts with the idea that electrons repel each other and assumes students can draw Lewis diagrams. All of the other bullets in the lower boxes must be *constructed* in the minds of students. In a guided-inquiry activity, students may explore the arrangement of 2, 3, 4, 5, or 6 electron domains to reach maximum distance. They may look at examples of molecules and Lewis diagrams to determine the definition of "electron domain." They may examine molecular models and Lewis diagrams to discover the "families" of molecular shapes and the modified shapes that occur when lone pairs replace bonds.

Connections to the AP Chemistry Curriculum Framework

Essential knowledge 2.C.4: The localized electron bonding model describes and predicts molecular geometry using Lewis diagrams and the VSEPR model.

Student Learning Outcomes

As a result of this lesson, students should be able to draw a Lewis diagram of a molecule (or ion) and use this diagram to:

- predict, along with VSEPR, the geometry of molecules [LO 2.21, *see* SP 1.4].
- draw a three-dimensional representation of a molecule using straight lines, hash marks, and wedges to indicate bonds in the plane of the paper, bonds going into the paper, and bonds coming out of the paper.

Student Prerequisite Knowledge

Before engaging in this lesson, students should be able to:

- state that electrons will repel each other because of Coulombic forces.
- draw the Lewis diagram of a molecule with 2, 3, 4, 5, or 6 atoms around a central atom.

For students who do not have this prerequisite knowledge, review the behavior of charge particles and Coulomb's Force law, the electron configurations of atoms, how to draw Lewis diagrams for atoms, and the rules for drawing Lewis diagrams for simple molecules.

Those students needing to refresh their knowledge of how like-charge particles repel may benefit from doing a PhET online activity on Coulomb's Force law (see http://phet.colorado.edu/).

Useful website

Students needing to refresh their knowledge on Lewis diagrams may benefit from doing the activity found at http://www.ausetute.com.au/lewisstr.html.

Useful website

Common Student Misconceptions

Many times students identify the incorrect molecular shape because they simply count the number of bonds present and forget that there may be lone pairs on the central atom affecting the shape. This often results in the misidentified molecular shapes of SO_2 and H_2O. Without drawing the Lewis diagrams, students may miss the lone pairs and identify these as linear species. When first learning about the VSEPR model, students will often ignore the lone pairs, or they might count a double bond as two bonds. If they are using a table such as the one shown on Handout 4, they will categorize the shape inaccurately if they have not correctly counted the number of lone pairs or bonds. The idea of electron domains will help to avoid this misconception. All groups of electrons repel, whether they are a lone pair or four electrons in a double bond; each group of electrons acts as a domain. To help students understand this concept, ask them to define “domain” as it is used in everyday language. (It is an area of influence, a region where something or things reside.) This may help them understand the number of electrons involved is irrelevant; it is just the groupings and their distribution that matter. Finally, students will often count lone pairs on the outermost atoms, in addition to those on the central atom, to determine the shape of the molecule. Activity 1 will help them visualize the central atom as the key to molecular shape.

Teacher Learning Outcomes

During this lesson, you will improve your skill as a facilitator by using questions to guide students to the discovery of the VSEPR model with minimal direct instruction. To do this, you must trust the process of inquiry, allow students to make mistakes along the way, and pose questions to make students confront their misconceptions and address them. For example, if a group is showing a four-bond structure with 90-degree angles, say to students, “This structure is very two-dimensional. Is there a way that you can take advantage of the third dimension to increase those bond angles?”

Teacher Prerequisite Knowledge

Useful website

Molecular shapes are determined by maximizing the attractive forces and minimizing the repulsive forces between atoms of a molecule, thus minimizing the potential energy. The electrons around a central atom in a molecule are attracted to the nuclei of the central and surrounding atoms but repelled by each other. Thus the molecule naturally finds a shape that brings the valence electron pairs as close to the nuclei as possible, while keeping them as far away as possible from other valence electrons. This model of molecular shape is called the Valence Shell Electron Pair Repulsion (VSEPR) model. The valence electron pairs around a central atom can be lone pairs or bonded pairs (or groups in the case of bonds of higher order). Each group or pair of electrons can be considered an electron domain. It is this number of electron domains around a central atom that dictates the shape of the molecule. For a review of VSEPR, see http://intro.chem.okstate.edu/1314f97/chapter9/vsepr.html.

Handout 4 shows the shapes predicted by the VSEPR model for various numbers of electron domains around a central atom. A three-dimensional representation of a molecule can be drawn using straight lines, hash marks, and wedges to indicate bonds in the plane of the paper, bonds going into the paper, and bonds coming out of the paper. The “families” or groups of shapes in the table are determined by the total number of electron domains (the sum of bonds and lone pairs; for example, methane can be classified as an AX_4E_0). It is important to note that a double bond does not represent two electron domains but only one because all of the electrons are in approximately the same region of space and therefore act as one domain. Molecules that have lone pairs on the central atom have similar bond angles to those with the same total number of electron domains; however, they are given a different name. This is because the lone pair electron domain(s) still repels the bonded electron domains, but it does not have an accompanying nucleus on the outer end of the domain. You could think of lone electron pairs as a difficult-to-detect branch because there is nothing with substantial mass at the end of it. The shape of a molecule is determined by two factors: first, the electronic repulsion of the electrons in bonds or lone electron pairs around a central atom; and second, the location of atoms around a central atom is a key part because the location of the nuclei of an atom can be detected.

Materials or Resources Needed

- Handouts 3 and 4
- String or elastic VSEPR sets with 2, 3, 4, 5, and 6 bonds (one for every three to five students): use approximately 50-cm-long pieces of string or elastic to represent bonds in a molecule; tie the pieces together at one end in one big knot (this intersection point will represent the center atom in a molecule)
- Four similarly sized balloons
- Molecular model sets (one for every group); if models are not available, toothpicks and different-color gum drops may be used to represent bonds and atoms
- Protractors

Activity 1: String Molecules

Step 1. Draw a Lewis diagram for methane (CH_4) on the board. Lewis diagrams generally are not used to show bond angles. The Lewis diagram of methane is drawn with 90° H-C-H bond angles. Ask students, “What angle does this diagram suggest between the C-H bonds of this molecule?” Students will answer 90°. Explain that a Lewis diagram for a molecule gives chemists a good idea of the connectivity of atoms and types and number of bonds, but just by being a flat, two-dimensional diagram, it cannot accurately represent the shape of a molecule because molecules exist in three-dimensional space. Ask, “What factors determine the three-dimensional shape of a simple molecule?”

Step 2. Lead a discussion about the attractive and repulsive forces involved in the molecule. The key in this portion of the lesson is to highlight the repulsion between sets of electrons. If students have not had a solid introduction to Coulombic forces, this would be a good opportunity to address the idea of attractive and repulsive forces decreasing as the distance between the charges increases.

Step 3. The following balloon activity is meant to provide an additional or optional opportunity for students who are struggling with visualizing the 3D tetrahedral arrangement on their own. Using four balloons tied together, demonstrate how the balloons occupy space and “repel” each other in a manner such that they are all equal distance from one another. The knot in the middle represents carbon, the central atom, and each balloon represents the electron density, a chemical bond, between carbon and hydrogen in a methane molecule. Students should see a tetrahedral arrangement of the balloons around carbon. Show them the “string molecules” with various numbers of strings attached. Tell students, “You are going to use strings, but think of each string representing a balloon.” Explain that the knot holding the strings together represents a central atom and the strings represent electron pairs coming off the central atom. Have students form small groups in various parts of the room (they will need space to move in order to experiment with different “bond” arrangements with their string sets). Be creative, but keep safety in mind as some students will need to be higher and some students need to be lower in order to achieve a three-dimensional shape; having a step stool or sturdy wooden box for one student to stand on may help facilitate the process. Direct the groups to each take a set, and hold the ends of the string to demonstrate what shape the molecule would need to have to maximize the distance between electron pairs *in three dimensions*. The groups should record their final shape by sketching the arrangement in their notes or on a group-reporting sheet.

This activity addresses multiple learning styles. Kinesthetic learners will benefit from the activity and movement in the room. Visual learners will be able to draw detailed sketches of the shapes. Auditory learners will have an opportunity to engage in conversation with group members as they work to find the best three-dimensional shape of the molecules.

As you circulate about the room, ensure that each group “discovers” each of the five shapes using the string molecules. Some groups may be stuck in a two-dimensional mindset—prompt them to utilize all three dimensions. This is interesting to do even with the trigonal planar molecule. Students will often grab the center atom and pull it up to make a pyramid shape. If they do, you can discuss whether that provides an advantage: Do the bond angles increase or decrease when they do that? What force moves that atom out of the plane? As you circulate, ask the groups about symmetry and/or bond angles within the molecule: “Are the bond angles less than 90°, or are they greater than 90°?”

Step 4. Collect the string molecule sets from the groups. Provide students (either on the board or with a handout) the names of each shape: linear, trigonal planar, tetrahedral, trigonal bipyramidal, and octahedral. Have them match each of their string-molecule shapes to one of the names. Students should be able to explain how each shape is described by the name. Ask the groups to describe how they matched the shape name to a drawing. Answers:

- *linear:* The three atoms form a line.
- *trigonal planar:* The three outer atoms form a triangle; the molecule is flat or “in a plane.”
- *tetrahedral:* The four outer atoms form a solid figure with four sides.
- *trigonal bipyramidal:* The five outer atoms form a three-sided pyramid on the top and a three-sided pyramid on the bottom.
- *octahedral:* The six outer atoms form a solid figure with eight sides.

Step 5. Students draw Lewis structures for five molecules, one to correspond with each shape. Students then work with a molecular model kit and build the molecules drawn in the Lewis structures. Students should predict the bond angles from the models and then measure the angle between bonds in each of their string shapes. It may help to hold up molecular models of the different shapes or have students recreate their string molecule for each shape. Students should use a protractor to measure the angles between three "atoms." Refer them back to the Lewis diagram of methane and ask, "Does a two-dimensional square shape or a 3D tetrahedral shape provide more space between the chemical bonds (the electron density)?"

Formative Assessment

As students are working on their string molecules, move around the room and check for student understanding by asking questions. If student groups are developing the correct shapes, ask them to justify why the shape is correct. If they are not getting the correct shapes, ask them guiding questions that focus on the repulsion of the electron pairs. Possible sample questions include "How many bonded pairs of electrons and lone pairs are around the central atom?" and "When all the electron pairs repulse each other, what is the maximum distance they will be from one another?"

Reflection on Formative Assessment

At the conclusion of this activity, students should have a good understanding of the origin of the names of all five basic molecular shapes. If students are not able to identify the names of the shapes, use classroom models to demonstrate each shape and state the name of the shape for the class. If necessary, review the terminology of geometric shapes. For example, octahedral molecular geometry describes the shape of compounds wherein six atoms or groups of atoms are symmetrically arranged around a central atom, defining the vertices of an octahedron. An octahedron has eight faces. The prefix *octa* means "eight."

Activity 2: Molecular Models

Handout 3

Step 1. Form small groups of students, and give the groups a molecular model kit and a copy of Handout 3. Have students draw Lewis diagrams for the molecules on the handout and then build each molecule, making sure to represent all of the atoms with the correct color code listed in the kit and to use the correct number of bonds. Monitor this process to make sure the Lewis structures are correct and the molecular models are properly constructed. When checking the groups' models, if the colors and numbers of bonds used are incorrect, first ask students what their model represents, and then suggest it be redone to be the correct model.

Step 2. Student groups sort the molecular models into categories based on shape and/or the Lewis diagram. They should be prepared to justify the name of their categories with a list of specific characteristics that would qualify a molecule to belong to the chosen category.

Step 3. Encourage students to move around the room and view the work the other groups have done in categorizing the molecules. One member of each group should stay with their models and categories in order to explain their work to visiting groups. Circulate and listen to students' explanations. They should use either similar bond angles or similar numbers of electron domains as justification for their categories. At this point, some groups may not have the molecules sorted correctly, but in the next step, they will have a chance to make corrections.

Step 4. After two or three minutes of sharing, direct the groups to reconvene and revise their categories based on what they saw in the other groups. This should result in students organizing the shapes into five categories, based on the five shapes developed in Activity 1. Even molecules with lone pairs on the center atom should be in the proper category. Check on each group to make sure students have the molecules sorted correctly at this point. It may be helpful to ask students if invisible pairs should be included and why or why not. If necessary, point out that a lone pair is "invisible" on the molecular model, but it is still a pair of electrons repelling like a bond. This will help students realize the Lewis diagrams are an important resource in determining molecular shape.

Step 5. Introduce the concept of *electron domain*, and explain to students that the categories they constructed are based on the number of electron domains around a central atom. Prompt the groups to discuss what constitutes an electron domain: Does a lone pair of electrons count as a domain? What evidence from their molecular model categories and/or Lewis diagrams do they have to support that? Does a double bond count as one electron domain or two? Do lone pairs on surrounding atoms count as electron domains? Have students write a one-sentence definition of "electron domain" and report out to the class. Guide the class to a single definition.

Handout 4

Step 6. Distribute Handout 4 to provide students the molecular shape names, diagrams, and a description of electron domains and bond angles. This information can also be found by accessing the following URLs:

- http://en.wikipedia.org/wiki/Molecular_geometry
- http://www.google.com/search?q=vsepr+shapes&hl=en&client=safari&rls=en&prmd=imvns&tbm=isch&tbo=u&source=univ&sa=X&ei=WgF-UP7AJpPm9gTEvYDYCg&ved=0CCAQsAQ&biw=1112&bih=700

Step 7. Students should name the shape corresponding to each molecular model they built in their groups. They should identify the molecular shape names on their handout. As groups work, circulate around the room to informally check answers. If students have a molecule incorrectly identified, use guiding questions focusing on bond angles and/or the number of electron domains in order to steer them in the right direction. A guiding question might involve asking how many bonds are present and how many lone pairs are present on an individual molecule.

Step 8. Direct students to look at the bond angles in molecules containing lone pairs and to compare them to molecules with the same number of electron domains that are all bonds. Within their groups, students should discuss the trend in bond angles and propose an explanation. This is a complex concept, but students may say something about the lone pairs repelling more or pushing harder on the bonded pairs. Conduct a classroom discussion on the responses and how the lack of a positive nucleus on the other end of the lone pair causes those electrons to have a larger orbital cloud, which then affects the other electron domains to a greater extent.

Formative Assessment

At the completion of Activity 2, provide students with some practice in identifying the shapes and bond angles of given molecules. This could be done with small whiteboards, a chalkboard, large pieces of paper, etc., in pairs or individually. Ask students to justify their shape choice by the number of electron domains. Listen to students' answers and explanations and provide appropriate feedback such as, "Yes, correct," "Good explanation," or "Your analysis of the molecule is missing a key piece of information; please go back and re-count the number of electron domains."

Reflection on Formative Assessment

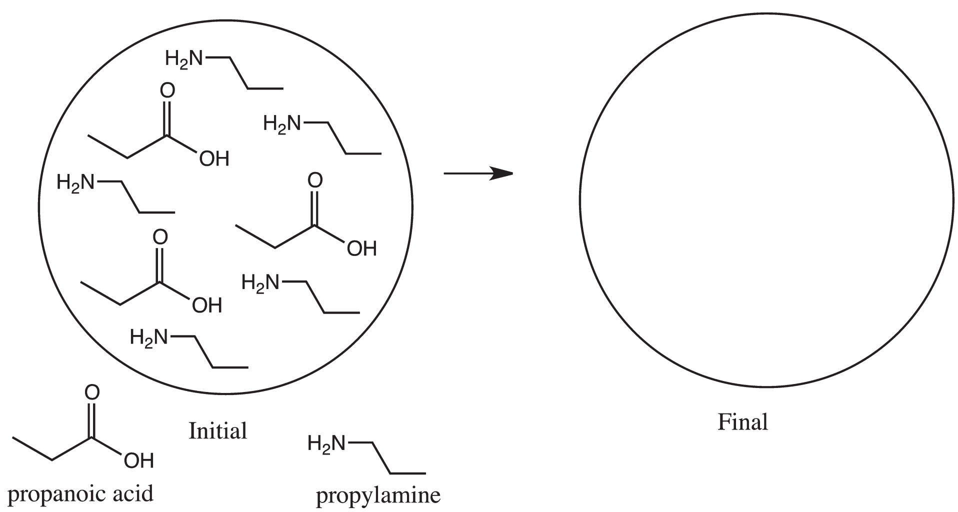
If students are not able to consistently identify the shape of a molecule correctly, try to identify where they are having difficulty. In some cases, the challenge is drawing the Lewis diagram itself. If that is the case, review the steps for drawing proper diagrams. If students are forgetting to count lone pairs as electron domains, remind them of the string molecules activity they did where *all* electron pairs were repelling each other. To reinforce what has been learned or to reteach the concepts for those that need it, interactive websites such as the PhET simulation "Molecule Shapes" may be a useful tool. The PhET computer simulation should be accompanied by a paper-and-pencil tutorial developed to help students use the simulation in a manner consistent with guided inquiry.

Summative Assessment

This summative assessment addresses Science Practice 1 using representations and models, Science Practice 2 using mathematics appropriately, and Learning Objectives 1.4, 1.17, 1.18, 2.21, and 3.4.

14.8 g of gas phase propanoic acid (C_2H_5COOH) is mixed with 14.8 g of gas phase propylamine ($C_3H_7NH_2$).

a) Write a balanced chemical equation for this reaction.
b) Which reactant serves as the limiting reactant?
c) Calculate the number of grams of the reactant that remains unreacted.
d) Draw Lewis diagrams for propanoic acid and propylamine.
e) Use VSEPR theory to draw a three-dimensional diagram of propanoic acid and a three-dimensional diagram of propylamine.
f) Determine the bond angles and the geometry of the atoms attached to the carbonyl carbon in propanoic acid.
g) Use VSEPR theory to determine the bond angles and the geometry of the atoms attached to the nitrogen atom in propylamine.
h) Given the following particle-level diagram of the number of molecules of propanoic acid and propylamine just prior to the reaction, determine what the diagram will look like at the end of the reaction. Consider the circle to be a closed system.



Scoring Guideline (worth 20 total points)

a. 1 point for each product and 1 point for the correctly balanced equation (3 points total)

b. 2 points for work and 1 point for the answer with units (3 points total)

c. 2 points for work and 1 point for the answer with units (calculation will be based on the answer to b; if the wrong limiting reactant is chosen, then the answer to c must be consistent) (3 points total)

d. 1 point for each Lewis diagram (2 points total)

e. 1 point for each diagram (2 points total)

f. 1 point for the correct geometry and 1 point for the bond angle (2 points total)

g. 1 point for the correct geometry and 1 point for the bond angle (2 points total)

h. 1 point for the correct drawing of the product, 1 point for the correct number (3) of the product, 1 point for the correct number of unreacted propylamine (3 points total)

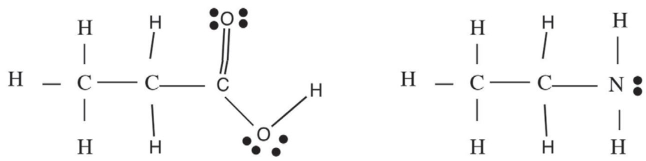
Answers:

a. $C_2H_5COOH(g) + C_3H_7NH_2(g) \rightarrow C_3H_7NH_3^+, C_2H_5COO^-(s)$

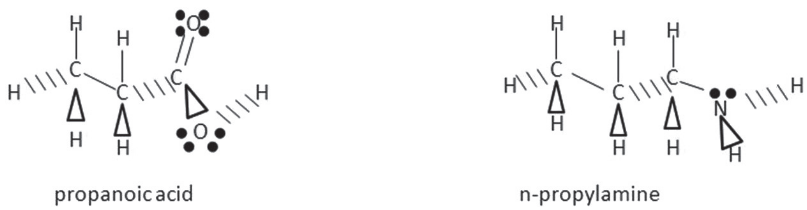
b. 14.8 g propylamine × (1mol/59.1 g) = 0.250 mol propylamine
14.8 g propanoic acid × (1 mol/74.08 g) = 0.200 mol propanoic acid
The balanced chemical equation indicates a 1:1 ratio of propanoic acid reacting with of propylamine. Therefore, propylamine is present in excess. 0.200 mol of propylamine reacts with 0.200 mol of propanoic acid, leaving 0.050 mol of propylamine unreacted. Propanoic acid serves as the limiting reactant.

c. 0.050 mole of propylamine × (59.1 g/1 mol) = 2.96 g propylamine remains un-reacted

d.



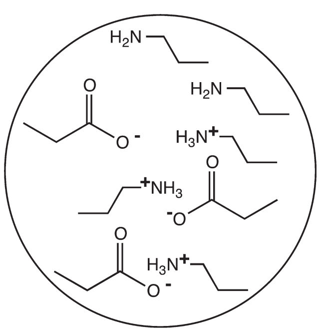
e.



f. C-C-O and O-C-O 120°, trigonal planar

g. C-N-H and H-N-H 107°, pyramidal

h. Three molecules of propanoic acid react with three molecules of propylamine. Two molecules of propylamine remain un-reacted. Three "units" of $C_2H_5COO^-$, $C_3H_7NH_3^+$ form.



Final

References

Asterhan, C. S. C., and B. B. Schwarz. 2007, “The Effects of Monological and Dialogical Argumentation on Concept Learning in Evolutionary Theory.” *Journal of Educational Psychology* 99: 626–639.

BouJaoude, S., and H. Barakat. 2000, “Secondary School Students’ Difficulties with Stoichiometry.” *School Science Review* 81, no. 296: 91–98.

Chiu, M. M. 2004. “Adapting Teacher Interventions to Student Needs During Cooperative Learning.” *American Educational Research Journal* 41: 365–399.

The College Board. “Inquiry Instruction in the AP Science Classroom: An Approach to Teaching and Learning.” Accessed December 11, 2012. http://media.collegeboard.com/digitalServices/pdf/ap/AP-Inquiry-Statement_Final_4-21-11.pdf.

Epstein, M. L., A. D. Lazarus, T. B. Calvano, K. A. Matthews, R. A. Hendel, B. B. Epstein, et al. 2002. “Immediate Feedback Assessment Technique Promotes Learning and Corrects Inaccurate First Responses.” *The Psychological Record* 52: 187–201.

Huddle, P. A., and A. E. Pillay. 1996. “An In-Depth Study of Misconceptions in Stoichiometry and Chemical Equilibrium at a South African University.” *Journal of Research in Science Teaching* 33: 65–77.

Lazonby, J. N., J. E. Morris, and D. J. Waddington. 1982. “The Muddlesome Mole.” *Education in Chemistry*, July 1982: 109–111.

Livermore, A. H. 1964. “The Process Approach of the AAAS Commission on Science Education.” *Journal of Research in Science Teaching* 2, no. 4: 271–282.

Mitchell, I. J., and R. F. Gunstone. 1984, “Some Student Conceptions Brought to the Study of Stoichiometry.” *Research in Science Education* 14, no. 1: 78–88.

Osborne, J. 2010. “Arguing to Learn in Science: The Role of Collaborative, Critical Discourse.” *Science* 328: 463–466.

Schmidt H.-J. 1990. “Secondary School Students’ Strategies in Stoichiometry.” *International Journal of Science Education* 12, no. 4: 457–471.

Yelkur, M. 2005. “Immediate Feedback Assessment Technique (IF-AT): Enhancing Collaborative Learning while Providing Immediate Feedback.” *MMA Fall Educators’ Conference*. Accessed December 11, 2012. http://www.epsteineducation.com/home/articles/file/Enhancing%20Collaborative%20Learning%20While%20Providing%20Immediate%20Feedback.pdf.

Zohar, A., and F. Nemet. 2002. "Fostering Students' Knowledge and Argumentation Skills through Dilemmas in Human Genetics." *Journal of Research in Science Teaching* 39: 35–62.

Resources

Abraham, M. R., and J. W. Renner. 1986. "The Sequence of Learning Cycle Activities in High School Chemistry." *Journal of Research in Science Teaching* 23, no. 2: 121–143.

Abraham, M. R. 2005. "Inquiry and the Learning Cycle Approach." In *Chemists' Guide to Effective Teaching,* ed. N. J. Pienta, M. M. Cooper, and T. J. Greenbowe (Upper Saddle River, NJ: Prentice Hall), 41–52.

Calatayud, M., S. L Bárcenas, and C. Furió-Más. 2007. "Surveying Students' Conceptual and Procedural Knowledge of Acid–Base Behavior of Substances." *Journal of Chemical Education* 84, no. 10: 1717.

Ivins, J. E. 1986. "A Comparison of the Effects of Two Instructional Sequences Involving Science Laboratory Activities." *University of Cincinnati Dissertation Abstracts* 46, no. 8: 2254A.

Lawson, A. E., M. R. Abraham, et al. 1989. "A Theory of Instruction: Using the Learning Cycle to Teach Science Concepts and Thinking Skills [Monograph, Number One]." Kansas State University, Manhattan, KS, National Association for Research in Science Teaching.

Lott, G. W. 1983. "The Effect of Inquiry Teaching and Advanced Organizers upon Student Outcomes in Science Education." *Journal of Research in Science Teaching* 20, no. 5: 437–451.

McComas III, W. F. 1992. "The Nature of Exemplary Practice in Secondary School Science Laboratory Instruction: A Case Study Approach." *University of Iowa* 52, no. 12: 4284A.

Raghubir, K. P. 1979. "The Laboratory-Investigative Approach to Science Instruction." *Journal of Research in Science Teaching* 16, no. 1: 13–18.

Renner, J. W. 1985. "The Learning Cycle and Secondary School Science Teaching." Norman, OK: University of Oklahoma Press.

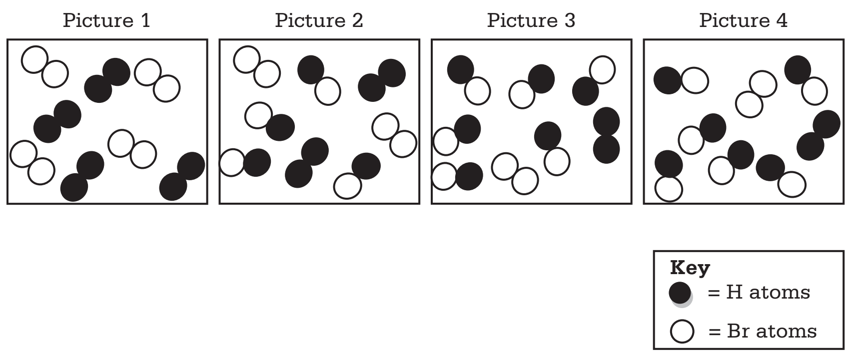
Trout, L., ed. 2012. *POGIL Activities for High School Chemistry.* Batavia, IL: Flinn Scientific, Inc.

Handout 1

Understanding the Meaning of a Balanced Chemical Equation

Information A:

We often use a variety of representations for chemical reactions. One is to use drawings or "cartoons" to represent what is happening at a molecular and atomic level.



1. What are the names of the substances represented in Picture 1?

2. a. What are the formulas for the substances represented in Picture 1?

   b. How did you decide on what the formulas should be?

3. What changes do you notice when you compare Pictures 1 and 2?

4. a. What formula would you use to identify the new substance formed in Picture 2?

   b. What name would you use for this substance?

Information B:

It would be awkward and time consuming to represent all chemical reactions with drawings. What we need is a way to notate a chemical reaction in a concise manner, which also conveys the information we need to understand about the process that happened.

5. What materials are present before any reaction happens (Picture 1)?

6. What materials are present after the reaction begins (Picture 2)?

7. New materials that are formed from reactants are called products. What product(s) forms during this reaction?

8. What materials are present in Pictures 3 and 4?

9. Identify the reactants and products present in Pictures 1, 2, 3, and 4 using the table below.

	Reactants	Products
Picture 1		
Picture 2		
Picture 3		
Picture 4		

10. In describing chemical reactions, scientists are interested in the changes that take place during the chemical reaction. Use formulas and symbols to describe the reaction represented by the pictures. An arrow is used to indicate the change from reactants to products. (Write a chemical-reaction equation. In this step, just focus on the identities of the substances.)

Information C:

In addition to identifying the substances involved in a chemical reaction, a chemical equation should also indicate the relative amounts of substances involved. We know from the Law of Conservation of Matter that the number of atoms and electrons, etc., has to be the same at the beginning and end of the reaction. Look again at the pictures representing the reaction.

11. How many of each reactant molecule are present at the beginning of the reaction (Picture 1)?

12. How many of each reactant and product molecule are present in Picture 2?

13. Identify the differences in the amounts of each species in Pictures 1 and 2.

    a. How many reactant molecules were used up?

b. How many product molecules were formed?

c. Write a chemical-reaction equation indicating the change that happened from Picture 1 to Picture 2. Your equation should indicate how many of each reactant was consumed and how many of each product was produced in going from Picture 1 to Picture 2.

14. How many molecules of each reactant and product are present in Picture 3?

15. Identify the differences in the amounts of each species in Pictures 2 and 3.

    a. How many additional reactant molecules were used up?

    b. How many additional product molecules were formed?

    c. Write a chemical-reaction equation that indicates the change that happened from Picture 2 to Picture 3. Your equation should indicate how many of each reactant was consumed and how many of each product was produced in going from Picture 2 to Picture 3.

16. Compare the equation you wrote for question 13 and the equation you wrote for question 15. How are they similar? How are they different?

17. The ratio of reactant and product molecules is what is important in a chemical-reaction equation. By convention, most chemical-reaction equations are written in terms of the lowest whole number coefficients. Write the "conventional" chemical-reaction equation for the reaction represented in the drawings.

18. Look at all three chemical-reaction equations that you wrote.

    a. What is true about the number of hydrogen atoms on each side of the reaction arrow?

    b. What is true about the number of bromine atoms on each side of the reaction arrow?

    c. As a group, write a statement using the Law of Conservation of Mass to explain why a chemical-reaction equation must contain equal numbers of atoms on each side to be "balanced."

Handout 1 Answer Key

Information A:

1. hydrogen and bromine
2a. H_2 and Br_2
2b. It should be something related to the symbols and the numbers of particles attached to each other.
3. Some of the H_2 and Br_2 molecules have gone away, and a new substance has formed.
4a. HBr
4b. hydrogen bromide

Information B:

5. H_2 and Br_2
6. H_2, Br_2, and HBr
7. HBr
8. H_2, Br_2, and HBr
9.

	Reactants	Products
Picture 1	$H_2 + Br_2$	None
Picture 2	$H_2 + Br_2$	HBr
Picture 3	$H_2 + Br_2$	HBr
Picture 4	$H_2 + Br_2$	HBr

10. $H_2 + Br_2 \rightarrow HBr$

Information C:

11. 4 H_2 ,4 Br_2
12. 2 H_2 ,2 Br_2 ,4 HBr
13a. 2 H_2 ,2 Br_2
13b. 4 HBr
13c. $2\ H_2 + 2\ Br_2 \rightarrow 4\ HBr$
14. 1 H_2 ,1 Br_2 ,6 HBr
15a. 1 H_2 ,1 Br_2
15b. 2 HBr
15c. $1\ H_2 + 1\ Br_2 \rightarrow 2\ HBr$ (Ones (1) before the molecules are optional.)
16. They have the same components and the same ratios, but the absolute numbers are different.
17. $H_2 + Br_2 \rightarrow 2\ HBr$ (Ones (1) before the molecules are optional.)
18a. The same number of hydrogen atoms is present on each side of the reaction arrow (either two or four depending on the equation).
18b. The same number of hydrogen atoms is present on each side of the reaction arrow (either two or four depending on the equation).
18c. The Law of Conservation of Mass says matter cannot be created or destroyed, only change forms. In a chemical reaction, the way the atoms are connected can change, but the overall number of atoms must stay the same.

Handout 2

Acid-Base Neutralization Reactions

Beginning Question: When an acid-base neutralization reaction occurs, what factors are important in determining the initial amount or concentration of the acid or base?

Goal: A computer simulation is used to explore what variables play an important part in determining the initial concentration or the volume of an acid or base involved in an acid-base neutralization reaction.

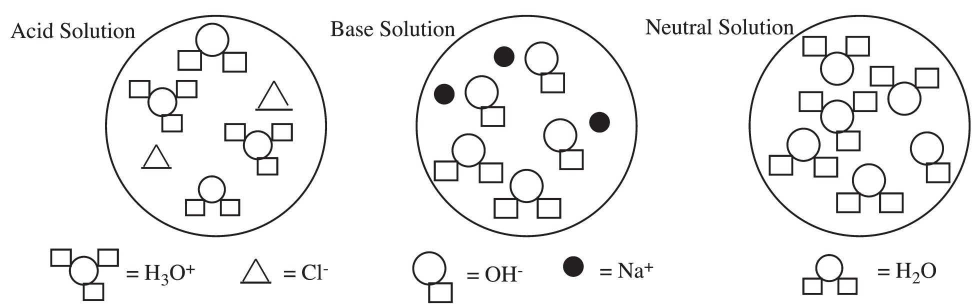
Model 1: Hydrochloric acid reacts with aqueous sodium hydroxide

$$HCl(aq) + NaOH(aq) \rightarrow NaCl(aq) + H_2O(l)$$

In general, an acid reacts with a base to form a salt and water. Given a base solution with an unknown concentration, we can neutralize this base solution by adding a known amount and volume of acid. An indicator will change color and let us know when the acid has neutralized the base. In an acid-base titration, we are not concerned about the amounts of products formed (although that can be determined); we are focused on the initial volumes and concentrations of the acid and base as they determine the amounts, which will be needed.

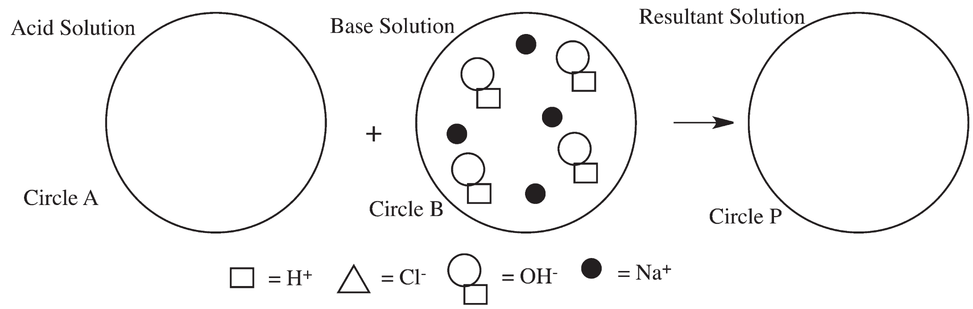
A balanced chemical equation provides quantitative information about how acids and bases react to form product(s). Atoms are neither created nor destroyed during a chemical reaction. The number and kind of each element in the reactant and product sides of a balanced chemical equation must be identical.

Model 2: A representation of solutions of an acid, a base, and water (a neutral) at the atom level



Activity 1: It is useful to know how much of reactant A is required to react with reactant B. The following diagram represents an atom-level view of a small portion of an acid, HCl(aq), and a base, NaOH(aq). If we want to neutralize the entire base present, how much acid must initially be present? (Note: Use H^+ to represent H_3O^+.)

- Complete the diagram by placing the appropriate number and kind of atoms in Circle A, representing the acid solution, and Circle P, representing the resultant solution when the acid and base solutions react. In this diagram, we are omitting the water molecules in the acid and base solutions. However, do not ignore any new water molecules produced in Circle P.



- At the point when an acid neutralizes a base, what can you say about the initial number of hydrogen ions and initial hydroxide ions relative to the resultant solution?

Activity 2: Using a computer simulation, design a series of experiments to identify and investigate variables and relationships associated with a strong acid-strong base titration. At least three acids and three bases should be included in the investigation. Two of the acids should be diprotic acids and two bases should be $M(OH)_2$ type bases. Determine a question you and your partner want to answer about acid-base reactions. Ensure that your question involves the use of different acids and bases, as well as different amounts and concentrations of each in the investigation. Make a data table for each specific acid-base titration reaction. You should do at least three titrations using different initial concentrations. Share your data with the rest of the class by putting them on the board or in a class data sheet.

Perform the Simulation for Your Investigation:

Steps 1–8 will help you complete the simulation found at the following URL: http://group.chem.iastate.edu/Greenbowe/sections/projectfolder/flashfiles/stoichiometry/acid_base.html

1. Open the simulation. It provides a simple way to explore what occurs when acids react with bases.
2. Become familiar with how the simulation works by following the onscreen directions. Complete Steps 1 through 4. Select HCl as your acid and NaOH as your base.
3. Write a balanced molecular chemical equation for the reaction of hydrochloric acid with aqueous sodium hydroxide.
4. Fill the buret with acid. Automatically, the Erlenmeyer flask will fill with base. The computer simulation will assign a molarity and volume to the base. This simulation does not allow you to alter the provided molarity and volume. The goal is to determine the molarity of the acid.
5. Select bromothymol blue as the indicator. When titrating with bromothymol blue indicator, the color blue indicates alkaline, the color yellow indicates acidic, and the color green indicates neutral.
6. Record the initial volume and concentration of the base, sodium hydroxide. Calculate the moles of sodium hydroxide present.
7. Click on the slider bar that adds acid to the flask. Carefully move the slider bar and add acid from the buret to the flask until the indicator changes to a green color. Most likely, you will exceed the end point.
8. Do not “reset” the titration (the “Reset” button will clear all parameters). Instead, click on the “Concordant Values” button; this maintains your current concentrations of base and acid and enables you to quickly do another titration. Use the slider bar to get close to the volume, and then use the “drops” button to add drops. The remaining steps will help you calculate the values you need.
9. When you have reached the end point of the titration, record the volume of acid that was required to react with all of the base present. At this point, how do you know the base has been neutralized by the added acid?

10. Use your calculated value of the number of moles of sodium hydroxide present from Step 6 and the balanced chemical equation from Step 3 to calculate the number of moles of hydrochloric acid added. You have already calculated the number of moles of sodium hydroxide present. Calculate the number of moles of hydrochloric acid added at neutralization.
11. Calculate the molarity of the acid and enter the value in the box in the simulation. The computer simulation will indicate if your answer is correct or incorrect. If your value is incorrect, you will need to click on the "Concordant Values" button. Re-run the experiment or check your calculations and then enter a new value for the molarity of the acid. Your teacher will help you construct a table of your data and a table for the class data.
12. When you are sure you have good data and correct calculations, share your data on the board.
13. Using all the class data, make a data table on your paper to report the number of moles of hydroxide ions initially present. Also report the class data of the number of moles of hydrogen ions or hydronium ions added at neutralization. Include these values in your data table.
14. Use the class data to make a graph. For example, plot the moles of sodium hydroxide present initially on the *y*-axis and moles of hydrochloric acid added to reach neutralization on the *x*-axis.
15. What patterns do you observe? What is the relationship between the initial number of moles of hydroxide ions present and the number of moles of hydrogen ions added when the base has been neutralized? What is the role of the balanced chemical equation in an acid-base titration?
16. Summarize how to calculate the molarity of the acid.

Organize Your Data:

- For example, if you investigate how an unknown concentration of sulfuric acid interacts with barium hydroxide, you might create the following data table:

Moles $Ba(OH)_2$	Moles OH^-	Moles H_3O^+	Moles H_2SO_4	M H_2SO_4

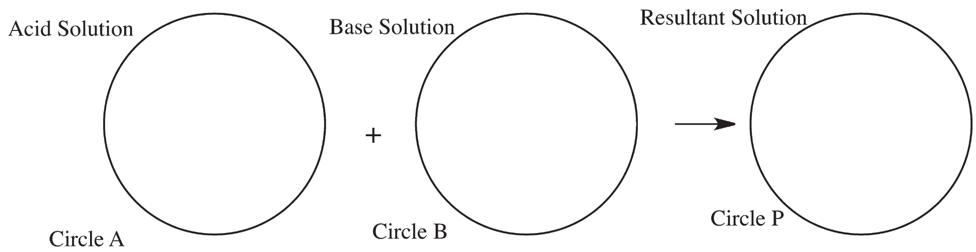
- For each type of acid-base reaction investigated, write a balanced chemical equation.
- You will need to determine the molarity of the solution in the buret for each investigation.

Data Analysis:

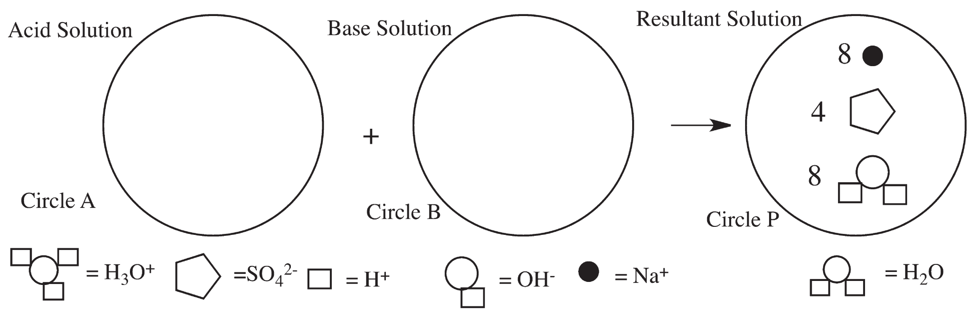
- Which two parameters yield a straight-line graph when plotted?
- What is the slope of the line?
- How is the slope of the line related to the balanced chemical equation?
- What factors are important when using an acid-base titration to determine the initial concentration of an acid or base that is not known?

Activity 3: Choose two of your acid-base titrations. Draw a picture diagram for each titration. In Circle A, use small circles, squares, and triangles to represent a small area of the acid solution. Assume complete ionization of the acid. The number and kinds of atoms and ions should be relative to your initial concentration of the acid.

You can assume the small volume is 1.0×10^{-21} L. Do the same for the base solution in Circle B. Circle P is what the resultant solution looks like when the acid and base solutions are combined in one flask.



Activity 4: The following circles in the diagram represent an atom-level view of a small portion of a sulfuric acid solution, a sodium hydroxide NaOH(*aq*) solution, and the resultant solution after the base has neutralized all of the acid. Complete the diagram by placing the appropriate number and kind of atoms in Circle A, representing the acid solution, and Circle B, representing the base solution. In the diagrams of the acid and base solution, water molecules are omitted. However, new water molecules produced by the reaction of the acid and base are shown in the resultant solution circle.



Activity 5: A 12.00 mL sample of a sulfuric acid solution used as battery acid (density = 1.245 g/mL) is diluted to 100.0 mL with water. A 10.00 mL sample of the diluted acid required 38.60 mL of 0.250 *M* NaOH(*aq*) for titration to the equivalence point.

- What is the molarity of the original sulfuric acid solution?
- What is the mass percentage of the sulfuric acid? If 0.250 *M* $Ba(OH)_2$(*aq*) was used instead of NaOH(*aq*), what volume of $Ba(OH)_2$(*aq*) would titrate the acid to the equivalence point? (Note: Use H^+ to represent H_3O^+.)

Handout 2 Answer Key

Organize Your Data:

Sample calculations

In experiment 1, 20.0 mL of an unknown concentration of $H_2SO_4(aq)$ solution is completely neutralized with 40.0 mL of 1.00 *M* $Ba(OH)_2(aq)$. In experiment 2, 40.0 mL of an unknown concentration of $H_2SO_4(aq)$ solution is completely neutralized with 40.0 mL of 1.00 *M* $Ba(OH)_2(aq)$. The balanced chemical equation is:

$H_2SO_4(aq) + Ba(OH)_2(aq) \rightarrow BaCl_2(aq) + 2H_2O(l)$

The concentration of the sulfuric acid can be calculated by determining the number of moles of hydroxide ions needed to react with all of the hydronium ions: # moles OH^- = # moles H_3O^+

	Moles $Ba(OH)_2$	Moles OH^-	Moles H_3O^+	Moles H_2SO_4	M H_2SO_4
Experiment 1	*0.0400 mol*	*0.0800 mol*	*0.0800 mol*	*0.0400 mol*	*2.00 M*
Experiment 2	*0.0400 mol*	*0.0800 mol*	*0.0800 mol*	*0.0400 mol*	*1.00 M*

For Expt 1: M = # moles H_2SO_4 / # L = 0.0400 mol/0.0200 L = 2.00 M

For Expt 2: M = # moles H_2SO_4 / # L = 0.0400 mol/0.0400 L = 1.00 M

Activity 5:

mol OH^- = 0.03860 L × 0.250 mol/L = 0.00965 mol OH^-

When all of the acid is neutralized, # mol OH^- = # mol H_3O^+

Therefore, 0.00965 mol OH^- = 0.00965 mol H_3O^+; this was the amount of H_3O^+ present in 10.00 mL. Therefore, there are 0.0965 mol H_3O^+ present in 100.0 mL.

The concentration of the diluted sulfuric acid:

$$0.0965 \text{ mol } H^+ \; \frac{1 \text{ mole } H_2SO_4}{2 \text{ mol } H^+} = 0.04825 \text{ mole } H_2SO_4$$

The concentration of the diluted sulfuric acid $\frac{0.04825 \text{ mole } H_2SO_4}{0.100 \text{ L}} = 0.4825\ M$

The volume of the original sulfuric acid solution is 12.00 mL.

The concentration of the original sulfuric acid can be calculated using: $M_1V_1 = M_2V_2$

$$M_1\ (0.01200\text{L}) = (0.4825\ M)(0.100\ \text{L})$$

$$M_1 = \frac{(0.4825M)(0.0100\,\text{L})}{0.01200\ \text{L}} = 4.02\ M$$

Handout 3

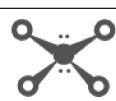
Molecule Building

1. Draw Lewis diagrams for each of the molecules listed below.
2. Use molecular modeling kits to build the molecules. Make sure your model is consistent with the number and types of bonds in the Lewis diagram.
3. After all models are constructed, sketch the 3D shape of the molecule and sort the molecules into categories based on shape and Lewis diagram. You must have at least two and no more than six categories. A category may be represented by only one molecule.
4. Be prepared to justify your categories with a list of characteristics that the molecules in each category have. Shape names will be added to the table later.

Molecule	Lewis Diagram	3D Sketch	Shape Name
H_2O			
SF_6			
CH_2O			
NH_3			
SO_2			
XeF_2			
CO_2			
PCl_5			
BeH_2			
BF_3			
XeF_4			
CH_4			
ClF_3			
BrF_5			

Handout 4

Molecular Geometry

Shape	Number of Bonds On Central Atom	Number of Lone Pairs on Central Atom	Bond Angles
Linear 	2	0	180°
Trigonal Planar 	3	0	120°
Bent 	2	1	<120°
Tetrahedral 	4	0	109.47°
Pyramidal 	3	1	<109.47°
Bent 	2	2	<109.47°
Trigonal Bipyramidal 	5	0	90 & 120°
See Saw 	4	1	<90 & <120°
T-Shaped 	3	2	<90 & <120°
Linear 	2	3	180°
Octahedral 	6	0	90°
Square Pyramid 	5	1	<90°
Square Planar 	4	2	90°

Contributors

Editors and Authors

Marian L. DeWane taught AP Chemistry and AP Environmental Science at Centennial High School in Boise, Idaho, until she accepted a position with the University of California–Irvine in 2010. She has served as a Reader, Table Leader, and Question Leader for the AP Chemistry Exam; she has also served as an AP consultant, facilitating workshops for AP teachers in the United States and internationally. Dr. DeWane authored two chapters and a lab in the AP Chemistry Lab Manual for the redesigned course, and she has edited and written for several AP Chemistry publications. She was chosen as a Presidential Scholar Teacher in 2001, 2004, and in 2009; she also received the Presidential Award for Excellence in Science Teaching in 2009.

Thomas J. Greenbowe has been a chemistry professor at Iowa State University since 1990, having previously served on the faculty at the University of Massachusetts–Dartmouth. He served as the Chair of the 2004 Biennial Conference on Chemical Education, Chair of the Division of Chemical Education of the American Chemical Society, and Chair of the 2009 Gordon Research Conference on Chemical Education Research and Practice. Dr. Greenbowe has served on the AP Chemistry Test Development Committee, as an AP consultant, and as a Reader, Table Leader, and Question Leader for the AP Chemistry Exam since 2007. He has published scholarly papers and facilitated Process Oriented Guided Inquiry Learning (POGIL) and Science Writing Heuristic (SWH) workshops for college faculty and science teachers in the United States and internationally. In 2012, he received the Iowa Regents Award for Faculty Excellence.

Authors

Michael R. Abraham served as a chemistry professor, Director of General Chemistry, and chemistry education researcher at the University of Oklahoma. He is the leading authority on guided-inquiry chemistry instruction, having co-authored a laboratory manual and seminal papers. He has worked on the Next Generation Chemistry Computer Simulation Project. Dr. Abraham's work has been translated into 10 different languages and cited worldwide over the past 40 years. In 2010, he received the American Chemical Society Award for Achievement for Research in the Teaching and Learning of Chemistry.

John I. Gelder is a chemistry professor at Oklahoma State University. He is a leading authority on instructional technology for chemistry instruction, incorporating guided-inquiry instruction. He has worked on the Next Generation Chemistry Computer Simulation Project. Dr. Gelder and his colleague Michael Abraham received a MERLOT Award for their Kinetic Molecular Simulator. He served two terms on the AP Chemistry Development Committee, and he has served as a Reader, Table Leader, Question Leader, Exam Leader, and Chief Reader for the AP Chemistry Exam. He has also served as an AP consultant, facilitating many workshops for AP Chemistry teachers. In 2011, he received the Oklahoma Regents Award for Faculty Excellence.

Renée S. Cole is an associate professor of chemistry at the University of Iowa, where she conducts research in chemistry education. She was previously a faculty member at the University of Central Missouri. She received the UCM College of Science & Technology Award for Excellence in Teaching in 2010 and the Missouri Governor's Award for Excellence in Education in 2009. Dr. Cole is one of the leading experts in the area of guided-inquiry instruction for upper-level college chemistry courses. She teaches a variety of chemistry courses and has taught a course in methods of teaching science for middle and high school teachers. Dr. Cole is interested in issues related to how students learn chemistry and how that can guide the design of instructional materials and teaching strategies. She is actively involved in the POGIL (Process Oriented Guided Inquiry Learning) project, conducting workshops and seminars around the United States and in Australia for instructors in both secondary and higher education. Dr. Cole is an associate editor for the ACS *Journal of Chemical Education*.

Laura Trout teaches at Lancaster Country Day School in Lancaster, Pa. She currently serves as the Editor in Chief for the High School Process Oriented Guided Inquiry Learning (POGIL) Initiative. She has written and implemented guided-inquiry activities for the high school chemistry classroom and facilitated POGIL workshops. Ms. Trout has designed two instructional products available from Flinn Scientific (Go Fish for an Ion Card Game and Gluep Production Lab).

Reviewers

Adele Mouakad, retired AP Chemistry teacher, San Juan, Puerto Rico

George E. Miller, retired chemistry professor, University California–Irvine