CHAPTER 2

Guided Inquiry in the Chemistry Laboratory Experience

Nearly every chemist can remember a special science laboratory activity they enjoyed doing. Often, it is the laboratory portion of a science course that provides some motivation to seek a career in science or engineering. *AP Chemistry Guided-Inquiry Experiments: Applying the Science Practices* provides 16 laboratory activities developed and classroom tested to incorporate best practices that support maximum student learning of chemistry content and skills. These best practices include an inquiry model of instruction, which differs substantially from the traditional model of laboratory learning. This chapter provides a brief introduction to inquiry in the AP Chemistry lab.

TRADITIONAL VERSUS INQUIRY LABS

In science, if you allow your students to experience scientific processes and to work with measuring devices, materials, and laboratory equipment, then laboratory experiences will promote a direct experience with science phenomena. Students benefit from lab experiences, although research indicates the amount of learning between traditional and inquiry labs varies. The traditional approach to laboratory activities has been to provide an opportunity for students to confirm a concept, identify an unknown chemical compound, or to verify a fact previously presented in a lecture. Lab manuals using this method are generally written in "cookbook" style, and students are expected to follow explicit, step-by-step directions. All students in the laboratory do the same procedure and only look for "the answer." This structure has led to traditional labs being referred to as verification labs.

By doing an experiment in a traditional manner, students may become proficient in basic manipulative skills, and they may have some insights that bolster their conceptual understanding. Educational research, however, tends to indicate the vast majority of students doing traditional laboratory experiments will often miss basic concepts. Traditional labs offer little hope that they develop any sense of the scientific process and the nature of science. Students in traditional labs miss the opportunity to develop the skill of designing an experiment to answer a research question. Finally, the prescriptive nature of the traditional lab often means students will be unable to apply what they have learned to slightly different situations.

A substantial body of chemical education research on students who have done inquiry labs indicates that students learn and retain more knowledge and skills using this approach than they do through comparable traditional labs. Research also shows increased levels of student engagement during laboratory. The labs in *AP Chemistry Guided-Inquiry Experiments: Applying the Science Practices* represent inquiry experiments and incorporate the AP science practices, which aim to develop investigative and scientific thought processes (see Chapter 3 for a discussion of the science practices).

DEFINING INQUIRY

Inquiry labs take a different instructional approach than the traditional labs discussed above, though they cover the same core chemistry concepts. Instead of seeking confirmation of concepts, inquiry-based labs allow students, with guidance, to observe phenomena, explore ideas, and find patterns allowing students to answer questions they have developed themselves. Several descriptions of inquiry exist.

One example was defined by Marshall D. Herron in 1971, which characterizes inquiry as structured, guided, or open.

- **Structured inquiry** involves answering a given question with a set procedure, but the answer is unknown and the students must analyze the data.
- **Guided inquiry** has a teacher-presented question, but the students must design their own procedures, compare data, and look for trends to answer the question.
- **Open inquiry** involves the students deciding on their own question in a topic area and designing their own experiment to answer that question.

Level of Inquiry	Question	Procedure	Solution
Confirmation (verification)	Teacher-presented	Teacher-presented	Teacher-presented
Structured inquiry	Teacher-presented	Teacher-presented	Student-generated
Guided inquiry	Teacher-presented	Student-generated	Student-generated
Open inquiry	Student-generated	Student-generated	Student-generated

Chart adapted from R. Bell, L. Smetana, and I. Binns, “Simplifying Inquiry Instruction” (The Science Teacher, October 2005)

In *Inquiry and National Science Education Standards: A Guide for Teaching and Learning*, the National Research Council (NRC) identified five essential components or elements of inquiry investigations:

1. Learners are engaged with scientifically relevant questions
2. Learners give priority to evidence
3. Learner explanations are based on the evidence they have generated
4. Learners make connections to prior scientific knowledge
5. Students communicate and justify their explanations

The degree of inquiry is based on the amount of self-direction by the student compared to directions provided by the teacher. This concept is summed up in the following table:

Essential Features of Classroom Inquiry and Their Variations

Essential Feature	Open Inquiry	Guided Inquiry	Structured Inquiry	Confirmation
1. Learner engages in scientifically oriented questions	Learner poses a question	Learner selects among questions, poses new questions	Learner sharpens or clarifies question provided by the teacher, materials, or other source	Learner engages in question provided by the teacher, materials, or other source
2. Learner gives priority to evidence in responding to questions	Learner determines what constitutes evidence and collects it	Learner is directed to collect certain data	Learner is given data and asked to analyze it	Learner is given the data and told how to analyze it
3. Learner formulates explanations from evidence	Learner formulates explanation after summarizing evidence	Learner is guided in process of formulating explanations from evidence	Learner is given possible ways to use evidence to formulate an explanation	Learner is provided with evidence and how to use evidence to formulate an explanation
4. Learner connects explanations to scientific knowledge	Learner independently examines other resources and forms links to explanations	Learner is directed toward areas and sources of scientific knowledge	Learner is given possible connections	
5. Learner communicates and justifies explanations	Learner forms reasonable and logical argument to communicate explanations	Learner is coached in development of communication	Learner is provided broad guidelines to use/sharpen communication	Learner is given steps and procedures for communication

More……...........Amount of Learner Self-Direction…………..…….Less

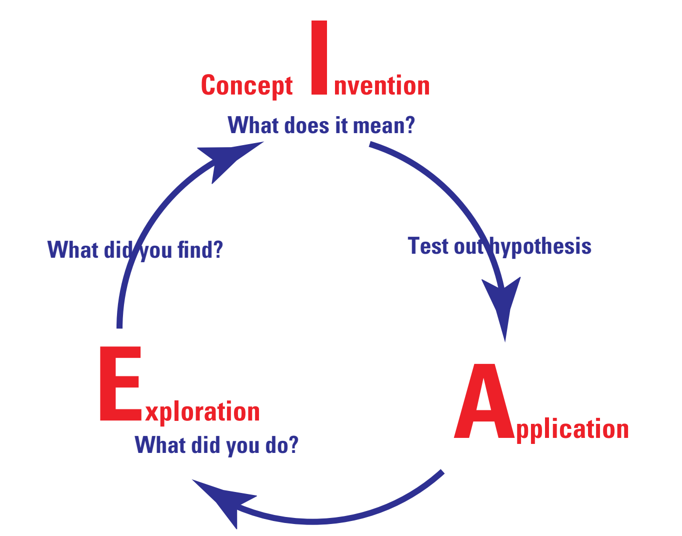
Less……………Amount of Direction from Teacher or Material…..More

From *Inquiry and the National Science Education Standards: A Guide for Teaching and Learning.* (National Academies Press, 2000)

Learning Cycles

All guided-inquiry instruction incorporates a learning cycle. A simple learning cycle proposed by Lawson and Abraham (1979) consists of exploration, concept invention, and application. All the labs in this manual have addressed either a part or all of a learning cycle. If you plan to adapt your own lab activities to inquiry, you need to be aware of what part(s) of the cycle is being used.

- **The exploration phase** allows students to collect and analyze data. Usually, by working in groups and sharing data, students explore several variables and construct tables and/or a graph. The experiment is designed to enable students to see a pattern to the data and, when possible, to experience something that runs counter to their way of thinking — a discrepant event.
- **The concept invention phase** allows the teacher to then lead a short discussion that introduces the concept and undertakes an interpretation of the data. The student then uses the data collected during exploration to develop a concept. This is a reversal of the traditional approach, which involves the teacher first telling students what a concept is, then going into the lab to confirm what the teacher said was true.
- **The application phase** allows students to use the concept to undertake a new activity or slightly different activity in which they apply the concept.



© POGIL

The three learning cycle phases are designed to adapt instruction to help students:

1. Become aware of their prior knowledge;
2. Foster cooperative learning and a safe, positive learning environment;
3. Compare new alternatives to their prior knowledge;
4. Connect it to what they already know;
5. Construct their own “new” knowledge; and
6. Apply the new knowledge in ways that are different from the situation in which it was learned.

Often a laboratory activity will involve only one or two phases of a learning cycle, and learning cycles can be short- or long-term. In some cases, one laboratory session might include the exploration and concept invention phases, and the next laboratory session might serve as the application phase.

Instructional Models for Chemistry Inquiry Lab Investigations

The AP Chemistry lab manual contains representative structured and guided inquiry experiments you might want to include in your laboratory program. It is important for teachers to know how to implement and conduct effective inquiry teaching and learning in the laboratory. There are several different models of inquiry in the laboratory. Three that influenced the development of the labs in this manual are the 5E or 7E model, Process Oriented Guided-Inquiry Learning (POGIL), and the Science Writing Heuristic (SWH). Many teachers are familiar with the 5E/7E model as it is widely used in lesson planning in K–12 education. POGIL and SWH are used widely in college and university general chemistry courses, and both approaches share common themes. In particular, they encompass a constructivist approach to student learning — one which explicitly acknowledges that students construct new meaning based on their new experiences and their prior knowledge.

Both the POGIL and SWH approaches:

- accommodate doing structured inquiry, guided inquiry, and open inquiry;
- incorporate a learning cycle in the activities;
- start the investigation with a Beginning Question or Question of the Day;
- encourage some degree of student input into the design of the experiment,
- utilize group work;
- include an instructor-facilitated whole-class discussion, leading students to construct concepts; and
- require that students do their work in a laboratory notebook.

Most college chemistry faculty members who are in charge of the general chemistry laboratory courses have their students write the results and interpretation of the lab investigation in a laboratory notebook using a traditional format: Title, Purpose, Procedure, Safety, Observations and Measurements, Analysis of Data, Conclusions, and Error Analysis. POGIL also uses this traditional format for the laboratory notebook, but adds a Question of the Day after the Title.

The SWH structures the laboratory notebook using a format that guides students to answer a series of directed questions. Then, through reflective writing, students continue to negotiate meaning from the experiment they conducted. More information about the SWH lab notebook structure and a rubric for grading an SWH lab notebook write-up are found in Chapter 4.

CONVERTING TRADITIONAL LABORATORY EXPERIMENTS TO INQUIRY EXPERIMENTS

The labs in this manual all represent inquiry labs. In addition to using some or all of these labs with their students, teachers may wish to do other labs as well. It is possible to modify any traditional lab in order to make it a structured-, guided-, or open-inquiry experiment. Designing and implementing inquiry-based labs that support student learning can be challenging. Teachers may want to consider collaborating with other teachers, attending workshops about inquiry-based labs (e.g., POGIL, SWH, or other chemistry education conferences or workshops), or consulting resources related to inquiry in the laboratory in order to become more skilled in implementing inquiry in their classrooms and laboratories. Some Web resources and references are listed at the end of the chapter.

This section provides general information about how teachers can go about modifying their own labs toward increased inquiry. For most teachers who currently do verification lab activities, a first step toward making the transition to including more inquiry in their curriculum is to do structured inquiry lab activities. For example, they might start by having students work in groups investigating a variable (mass, concentration, temperature) over a range and seeing what effect it has on a factor, pooling data, making a graph, and ultimately inferring an answer based on the graph of the pooled data.

To modify a cookbook lab, begin by exploring the lab by thinking about the following question as you read the lab: *What characteristics make this lab "cookbook" rather than inquiry?* Once you have a list of characteristics, write down three to five that you'd like to modify. It is a good idea to incorporate the NRC's summary of components of guided inquiry, listed earlier in this chapter, into this step. Ask yourself: *At what inquiry level is the lab currently? Toward what inquiry level do I want the lab to move?* Identify specific sections of your activity with one of the phases of the learning cycle. Remember, the important thing is that even making small changes can provide your students with more of an inquiry experience.

Three examples of how a teacher could go about modifying common cookbook experiments are explained below. Note that these are not detailed prescriptions for complete experiments but suggestions for how to think about inquiry modifications.

1. *Molar volume of a gas*. A traditional version of this lab asks students to determine the molar volume of a gas by combining hydrochloric acid with magnesium. Students are given a set amount of magnesium and a set procedure. A possible guided inquiry question could be as follows: How does the mass of magnesium ribbon used affect the molar volume of a gas? In the guided inquiry version, all students will choose to use a different amount of Mg to do the reaction. They can do several trials with different amounts of magnesium. They will all put their end results and calculated data on the board and analyze the data.
2. *Qualitative analysis of ions in solution.* In a typical, traditional version of this lab, students are given a series of known solutions and a set procedure for identifying various ions. After observing the reactions of the known solutions, students repeat the same procedure with an unknown solution. A possible inquiry-based version of this lab would involve giving students a set of test reagents and a series of known solutions and asking them to design procedures to distinguish between three or four ions. Different student groups could work with different known ions. Next, students could share their data and the procedures they designed in a whole-class discussion and then use their combined data and work together to design a procedure to identify the ions in an unknown containing several ions together.
3. *Electrochemistry — galvanic cells*. Traditionally, students are given a set procedure to construct a number of galvanic cells from various metals and solutions and measure the cell potential of each one. One more inquiry-based way to conduct this lab would entail students investigating different factors that affect cell potential, such as electrode identity or concentration of reactant solutions. Each group would study only one factor, and then

groups would come together to share data and discuss patterns. Finally students would be challenged to apply their learning to create the battery with the greatest cell potential.

Practical Criteria for Implementing Inquiry Laboratory Experiments

Frank Creegan (POGIL Project) and Tom Greenbowe (SWH Project) developed a list of criteria used to determine if a science laboratory activity is an inquiry activity. An activity does not have to include all of following criteria but it helps if the activity contains most of the criteria.

- The title of the experiment should not reveal the concept(s) to be discovered.
- Prior to doing the experiment, the outcome is known to the instructor but not to the students
- The prelaboratory session contains the following parts:
    - The instructor (and the laboratory manual) provides appropriate technical laboratory skills, demonstration of skills, and explicit safety procedures by direct instruction.
    - The activity should be structured so that the instructor (and the laboratory manual) does not teach the targeted concept prior to the students doing the experiment.
    - The introduction to the laboratory activity should have students review prerequisite knowledge, skills, and concepts necessary to develop an understanding of the targeted concept.
    - Students are encouraged to make predictions or estimates of what will happen during the lab.
- The activity should be structured to include all phases of a learning cycle (i.e., exploration, concept invention, application), or the activity should be structured to be one or two phases of the learning cycle for the targeted concept, with the other phase being done in the classroom or computer lab.
- The activity begins with a focus question, the "Question of the Day" (QOD) or the "Beginning Question" (cannot be a yes or no question).
- The laboratory manual provides information about the technical lab procedures and skills to be used.
- Students have some degree of input into the design of the experiment. The results obtained using the experimental design must provide information that enables students to answer the QOD.
- The activity uses observation or data collected to develop a theoretical construction rather than to confirm or verify a concept.
- Students work in groups on experiments that will contribute to the class data pool. All students are involved in experimental work. Results are written on the board, then added to a database or an electronic spreadsheet.
- Students use the class data to see a trend and then, with the help of an instructor, invent the target concept. When appropriate, the class data should be graphed.
- The experimental procedures, techniques, and equipment used are pre-tested so 90–100 percent of students can obtain reliable data.

- Students are able to construct an answer to the QOD with the guidance of the instructor rather than being told or having the answer verified by the instructor.
- The activity involves minimal instructor input during the experiment.
- The laboratory manual provides the framework for the activity. Sufficient information is provided for students to be able to understand what they are to accomplish for each experiment.
- Questions in the lab manual or verbal questions from the instructor may explicitly direct students to consult with their peers.
- The success of a guided-inquiry laboratory experience depends on the effective facilitation of the laboratory experience during the prelab and during the postlab discussion by a qualified instructor.

TEACHER ROLES

In a guided-inquiry laboratory, the instructor's main role is to serve as a facilitator who listens to students and asks guiding questions rather than providing answers. Thus if a student asks a question that can be answered through testing in the laboratory, rather than answering the question, the teacher can ask the student to think about what they could do to determine the answer themselves. A simple example is a student asking "Is this solution acidic?" to which the teacher, rather than replying "Yes" or "Why don't you check the pH", would say "What information do you need to determine if it is an acid? How can you find out?" Many teachers may find it difficult not to teach the subject first and review the whole concept being explored before the lab begins. In guided inquiry, though, the postlab is the most important part, as this is when you and your students analyze and make sense of observations and results. Students may be resistant to the guided-inquiry approach, particularly if they are used to more prescriptive labs. Student frustration can often be mitigated by explaining some of the benefits of guided-inquiry tasks like generating hypotheses and designing experimental procedures, including enhanced skills and understanding of content and greater ability to apply skills in more challenging college courses or in industry. Teachers are encouraged to "sell" inquiry to their students explicitly, especially at the beginning of the course.

Lab Components Requiring Direct Instruction

Safety and Technique

Guided-inquiry activities do require students to generate reliable and accurate data, so students must develop good laboratory techniques, which often must be taught through direct instruction. To meet this need, many teachers first present laboratory exercises to help students develop good laboratory technique and skills. Students are able to then use these techniques to perform inquiry-oriented experiments. Examples of skills taught by direct instruction include titration, suction filtration, and the use and standardization of a pH meter. Lab safety is also taught by direct instruction. It is vital to note that safe practices must not be abandoned, but reinforced, in the desire to allow students freedom to design their own experiments.

There are several ways you can ensure a safe, orderly, guided-inquiry laboratory environment. One technique that helps to frame the task students must accomplish is to limit the equipment the students can choose from to perform the lab. This can help make designing the lab more successful for students. Either having a cart with equipment, limited equipment at a lab station, or a lab check out system will work to provide constraints on what choices students have available to design their experiments. In some cases, it can be a useful tool to provide some unneeded equipment. This technique can focus student efforts and make each student think about the data they need to collect and what they will need to collect it.

Students should always be aware of the MSDS of any chemical used and know the procedures to follow in case of a spill or accident. This is true of any type of lab. Proper safety equipment should always be present and the teacher should ensure that all students are wearing required safety materials such as goggles.

Of course, safety is always important, so additional equipment should not prompt unsafe methods. After students write up their procedures, you should read and initial the student method. Students should briefly review safety aspects in their proposed methods. Once again, this step is present to ensure that proper safety is being followed. Chemicals should probably *not* be freely available to students to avoid unsafe combinations. All waste containers should be marked for the students to ensure proper handling of waste. Depending on the length of your class period, often a natural stopping point is after developing and refining the procedure, with the practical work performed the next day. If the lab goes over multiple days, keeping materials on a cart designated for a particular class helps to keep things organized. Another difference to keep in mind is that not all students will be doing the same thing in lab and students will be collaborating and comparing at the end of the lesson as they collect and share their data.

Students are often frustrated by a guided-inquiry approach and may simply want "the answer" if they have seldom experienced inquiry-oriented labs before. With positive reinforcement and encouragement, students will generally overcome their frustrations. The greatest success arises from exposure to inquiry from the elementary grades upward. If possible, it is important for the AP teachers to meet with other science teachers in their school and feeder schools to discuss the role of inquiry in preparation for *all* AP science courses. Establishing a science vertical team will aid in student preparedness for inquiry and hence for a successful AP experience.

WEB RESOURCES WITH INQUIRY INFORMATION

POGIL: *http://www.pogil.org/*

SWH: *http://avogadro.chem.iastate.edu/SWH/homepage.htm*

National Science Teachers' Association (NSTA): *http://www.nsta.org*

Journal of Chemical Education: *http://pubs.acs.org/journal/jceda8/*

REFERENCES

Bruck, Laura B., and Marcy H. Towns. "Preparing Students to Benefit from Inquiry-Based Activities in the Chemistry Laboratory: Guidelines and Suggestions." *Journal of Chemical Education* 86, no. 7 (2009): 820–822.

Bybee, Rodger W. *Science and Technology Education for the Elementary Years: Frameworks for Curriculum and Instruction*. Washington, DC: National Center for Improving Science Education, 1989.

Center for Science, Mathematics, and Engineering Education. *Inquiry and the National Science Education Standards: A Guide for Teaching and Learning*. Washington, DC: The National Academies Press, 2000.

College Board. *The AP Vertical Teams® Guide for Science*. New York: The College Board, 2009.

Criswell, B. "Framing Inquiry in High School Chemistry: Helping Students See the Bigger Picture." *Journal of Chemical Education* 89, no. 2 (2012): 199–205.

Eisenkraft, Arthur. "Expanding the 5E Model." *Science Teacher* 70, no. 6 (2003): 56–59.

Farrell, J.J., R.S. Moog, and J.N. Spencer. "A Guided Inquiry Chemistry Course." *Journal of Chemical Education* 76, no. 4 (1999): 570–574.

Herron, M.D. "The Nature of Scientific Enquiry." *School Review* 79, no. 2 (1971): 171–212.

Keys, Carolyn W., Brian Hand, Vaughn Prain, and Susan Collins. "Using the Science Writing Heuristic as a Tool for Learning from Laboratory Investigations in Secondary Science." *Journal of Research in Science Teaching* 36, no. 10 (1999): 1065–1084.

Rudd, J.A., T.J. Greenbowe, and B.M. Hand. "Using the Science Writing Heuristic to Improve Students' Understanding of General Equilibrium." *Journal of Chemical Education* 84, no. 12 (2007): 2007–2011.