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Guided-Inquiry Experiments for Physical Chemistry: The POGIL-PCL Model

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Supporting Information

ABSTRACT: The POGIL-PCL project implements the principles of process-oriented, guided-inquiry learning (POGIL) in order to improve student learning in the physical chemistry laboratory (PCL) course. The inquiry-based physical chemistry experiments being developed emphasize modeling of chemical phenomena. In each experiment, students work through at least two learning cycles in which they make predictions, collect data, model the data, and discuss its meaning. The design of the student laboratory experiences resembles the apprenticeship model of research because students carry out an experiment with faculty guidance to determine which parameters are best modified in subsequent trials of the same experiment. The POGIL-PCL model is illustrated using the example: "What are the kinetic parameters of a heterogeneous reaction?" Typical student results and responses are discussed.

KEYWORDS: *Upper-Division Undergraduate, Physical Chemistry, Inquiry-Based/Discovery Learning, Kinetics, Rate Law, Gases*

BACKGROUND AND INTRODUCTION

Laboratory courses should engage students in realistic scientific inquiry and problem-solving in addition to teaching students specific content and laboratory techniques. The American Chemical Society guidelines[1] for undergraduate chemistry programs explicitly call on faculty to use guided inquiry and collaborative learning for instruction. The guidelines single out the advantages of using "inquiry-driven and open-ended investigations"[1] for laboratory instruction. Inquiry experiments were found[2] to be more effective than verification experiments at achieving these goals based on student responses to an inventory of laboratory characteristics. For example, students were much more likely to rate inquiry experiments higher than verification experiments at requiring students to use evidence-based arguments. Allen et al.[3] noted that the cookbook nature of verification experiments can actually inhibit intellectual stimulation.

We present an approach to guided inquiry and collaborative learning in the physical chemistry laboratory through the POGIL (Process Oriented Guided Inquiry Learning) framework. Beyond the specific content, physical chemistry plays a key role in the intellectual development of students. Mastery of physical chemistry requires the synthesis of concepts from multiple disciplines: chemistry, physics, and mathematics. Achieving this mastery supports the development of interdisciplinary thinking that benefits students in their postcollege work. With the emphasis of POGIL on developing both content knowledge and process skills, its use in the physical chemistry laboratory provides an effective tool for student development at the transition from undergraduate work to graduate school or industry.

Physical chemistry laboratory classes typically adopt one of two textbooks[4,5] or self-publish manuals based on these texts or on experiments published[6] in the *Journal of Chemical Education*. Most of these experiments begin with a lengthy background section detailing theory, concepts, and equations. The background section is followed by a brief experimental section and then by instructions to determine some physical parameter or property. Final questions ask students to explain their results. Student reports often conclude with the percent difference between their results and the published results along with an appeal to human error to explain the difference.

The outcomes of these physical chemistry experiments are well-known to faculty and are often telegraphed to students before the lab work is started. Students often believe that the goal of a physical chemistry experiment is to reproduce those results, and developing an understanding of physical chemistry concepts is generally secondary. Frequently, student effort and attention for physical chemistry experiments is focused on how well their experimental results agree with published results.

Structural features of the physical chemistry laboratory distinguish it from the laboratory courses in, for example, general or organic chemistry. Experiment topics are less likely to be synchronized with lecture topics, in part due to limited laboratory instrumentation resources (for example, only one bomb calorimeter). At some institutions, students may take the physical chemistry laboratory course in a different term than the lecture courses. Certain topics, like kinetics, may be covered primarily in the laboratory because the underlying concepts are better understood in the context of student-generated data. Many experiments performed in the physical chemistry teaching laboratory reproduce an observation described in the classroom, such as the infrared spectrum of HCl. On the other hand, some phenomena discussed in physical chemistry lecture are difficult for students to reproduce in a teaching laboratory; examples include measurement of absolute entropy, angular

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wave functions of the hydrogen atom, or spin. Still other experiments require instrumentation and/or instructor expertise that lies outside the capacity of the institution, such as measuring the Joule−Thomson effect.

Several[7−9] efforts previously incorporated inquiry in general, organic, and physical chemistry laboratory courses. Participants in the Science Writing Heuristic (SWH) project[7] have developed and tested experiments for general and organic chemistry laboratory. Students carrying out SWH experiments devise a research question, postulate a conceptually based claim, and determine the measurements needed to support or reject this claim. Inquiry-driven experiments[8] developed for physical chemistry were explored by chemistry faculty at The College of the Holy Cross. The prelab work of each multiweek laboratory exercise required student groups to develop a research proposal based on a question posed by the instructors. The research group had access to a lab manual that provided experimental and theoretical background information. Once the research proposal was approved, students had two weeks to collect data and a third week to devote to data analysis. The resulting report was written in the form of a journal article. The Physical Chemistry Online (PCOL)[9] project led to the development of physical chemistry experiments and classroom exercises that students from different universities could choose to work on collaboratively via the Internet and e-mail. PCOL activities were designed to promote online collaboration among students and faculty as well as provide more open-ended questions for students to answer through their work. Students learned that they must share data in order to arrive at meaningful conclusions.

General and organic chemistry guided-inquiry experiments involving student collaboration were developed previously based on POGIL criteria.[10] POGIL provides a research-based learning environment in which students are guided to discover chemistry concepts using a learning cycle[11] construct, Exploration → Concept Invention → Application, and encouraged to practice process skills such as teamwork and communication. POGIL-based experiments are structured to follow this learning progression and actively encourage collaboration in the laboratory. These experiments[10] have outcomes known to the faculty, not the students, start with a research question posed by the instructor, and require students to pool data. The experiments are designed so that students should consistently obtain reliable data. Students are guided to the appropriate concepts, which are reinforced through careful questioning. To date, there has been no formal development of physical chemistry experiments based on POGIL principles.

POGIL-PCL, Process Oriented Guided Inquiry Learning—Physical Chemistry Laboratory, is a project developed to provide physical chemistry experiments that are inquiry-driven rather than verification-based and that follow a learning cycle. The experiments are designed so that they can be carried out at institutions of any size in either a whole-class or round-robin setting. POGIL-PCL experiments build on prior developmental work of The College of the Holy Cross, POGIL, SWH, and PCOL for the physical chemistry laboratory. In this work, we describe the general framework that we have developed for POGIL-PCL experiments, provide an illustrative example of this structure, and discuss the place of POGIL-PCL in the context of inquiry-based experiments.

THE STRUCTURE OF THE LABORATORY ACTIVITY

The POGIL-PCL experiment framework is diagrammed in Figure 1. The title of the experiment is a conceptual question to

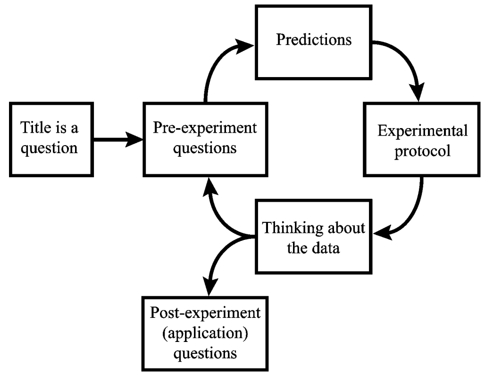

Figure 1. POGIL-PCL experiment template. POGIL-PCL experiments include multiple data-think cycles as shown in the middle of the figure and discussed in the text.

be answered by doing the experiment. The heart of the experiment is a set of “data-think cycles” in which students answer preparatory questions, make a prediction, follow a standard protocol (procedure) to test the prediction, and then analyze the data. The experiments are designed such that at least two cycles are needed to answer the title question for the experiment. Ultimately, students apply the concepts learned or probe the concepts more deeply in postexperiment questions. Each pass through the cycle immerses the students more deeply into the concept. The first data-think cycle generally focuses on a qualitative outcome, and successive cycles emphasize graphing data and quantitative modeling.

During a POGIL-PCL experiment, students work together in small groups or as a whole class. They make decisions or choices related to the experiment in real time, and they generate predictions of experimental outcomes before collecting data. Everyone follows the same protocol or procedure for collecting data, although frequently students divide the experiment among different groups and then pool data to arrive at answers to the experiment questions. After data has been collected, the students model the data using functions developed from a physical chemistry concept. Equations used to model data are introduced to students either just before or just after data collection. The “thinking about the data” questions require students to provide evidence-based explanations for their results. At several points in the cycle, the whole class may discuss a particular concept in greater detail or the appropriate choices for the next experiment.

The next section describes more fully one POGIL-PCL experiment in order to illustrate the structure depicted in Figure 1.

A POGIL-PCL EXAMPLE: WHAT ARE THE KINETIC PARAMETERS OF A HETEROGENEOUS REACTION?

The traditional version of the experiment *“What are the kinetic parameters of a heterogeneous reaction?”* is found in the *Journal of Chemical Education*[12] and the Halpern and McBane textbook.[4] The traditional version begins with several pages of discussion of the chemistry and kinetics of this reaction. Students are told the form of magnesium to study (ribbon), concentrations of hydrochloric acid to use, volumes and lengths of magnesium ribbon to mix in the reaction vessel, and quantity to measure (pressure) in order to follow the progress of the reaction. Following data collection, students are asked to calculate the reaction rate orders and the activation energy.

The POGIL-PCL variation of this experiment (Supporting Information) follows the experimental template of Figure 1 while

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still ensuring that the students determine the rate law and activation energy for this reaction. Students probe the reaction qualitatively during the first "data-think" cycle in order to examine the effect of the physical form of magnesium on the reaction rate. Based on the data they obtain, students (as a class) make decisions about the experiments they will perform in order to achieve a quantitative understanding of the process. For example, students are prompted to use their data to discuss which physical property of magnesium affects the reaction rate and which physical form of magnesium is best to use to investigate that property. A primary goal of POGIL-PCL experiments is to have students collect and analyze data together with the instructor in real time rather than collect all the data and subsequently do the analysis alone outside of lab, sometimes weeks after they have collected the data.

A detailed instructor's handbook (Supporting Information) accompanies each POGIL-PCL experiment. To an instructor implementing the experiment, this handbook provides timing estimates, answers to questions, and typical student predictions, data, and results. The experiment-specific handbook has critical prompts and reminders for the instructor to assist with facilitation of the experiment. The instructor's handbook also includes conceptual and process learning objectives for the experiment. In "What are the kinetic parameters of a heterogeneous reaction?", the learning objectives include

- Process objective: develop the ability to convert a relationship into a linear form and apply that relationship to measured quantities.
- Content objective: choose experimental parameters that allow determination of the rate law of an experiment.

These objectives are typically not provided to the students prior to performing the experiment.

The title of a POGIL-PCL experiment is a question that asks for more than the determination of a number, although that can certainly be an experimental goal in physical chemistry. The title for this experiment is "What are the kinetic parameters of a heterogeneous reaction?" Here, the answer refers to both the determination of which parameters are important for monitoring kinetics and the specific numerical values for this reaction. The question foreshadows the first data-think cycle in the experiment. A brief paragraph then introduces the question and provides some motivation for doing the experiment. This paragraph is not a detailed accounting of the conceptual learning outcomes.

Each experiment cycle begins with a set of pre-experiment questions or preparation questions (Box 1) that students answer in their lab notebooks before coming to the lab session. The pre-experiment questions focus on the protocol to a greater extent than do questions for later repetitions of the cycle. The students are assigned randomly to groups of three or four when they come to lab, and they discuss their answers to the pre-experiment questions in their groups. The role of the instructor is to facilitate the whole-class discussion of the pre-experiment questions preparing them to perform the first experiment.

A general experimental protocol (Box 2) describes the procedure common to each experiment in a "data-think" cycle. The protocol is designed to be broad; in this instance, the students are not given the concentrations, masses, or volumes to use. Once the experimental question is discussed, the instructor leads a discussion of the appropriate concentrations and volumes of HCl and of the actual amounts of Mg to use. The discussion is an opportunity for students to learn about decision making in the lab. For example, they begin to think about waste when determining how much solution to prepare while still meeting the needs of their group or the entire class.

Box 1. Example Experiment Preparation Questions To Begin the Experiment

1. What are the products of this reaction? Write the balanced chemical equation (both molecular and net ionic) for this reaction, including the states of reactants and products.
2. The "quantity", or measurable property, of a reactant or product is important when determining kinetics parameters. Such quantities might include but are not limited to concentration or something analogous to concentration, such as mass, pressure, volume, surface area, length, width, density, or something else. What is the appropriate quantity to use for each reactant and product in this reaction? Explain your choice.
3. Suggest at least one experimental method that could be used to follow the progress of this reaction, and justify your suggestion.
4. Sketch in your notebook a picture of what the apparatus used in the experiment might look like.
5. In your lab notebook before lab, calculate the pressure in both atm and mmHg exerted if 20.0 mL of 0.10 M HCl reacts with excess magnesium in a 125 mL flask at 298 K. What mass of magnesium reacts? What would be the pressure if 1.0 M HCl is used?

Whenever practical, POGIL-PCL experiments include student preparation of solutions and reagent systems as a component of the experimental work. The information provided to students includes limited information about this preparation because each class may make different decisions about which solutions, concentrations, and other systems are necessary to do the experiment. The expectation is that students will rely on prior knowledge to prepare correctly any solutions required, although some instructor guidance is typically needed. Stock solutions prepared by the instructor may be used to save time, but students must still decide on and perform appropriate dilutions.

For each data-think cycle, students predict an outcome before doing the experiment and then carry out the protocol to answer a question. The instructor's handbook includes a reminder to request this prediction in writing from the students. Here most students predict that increasing the mass of magnesium will increase the rate of the reaction. To test this prediction, students compare the rates of reaction for up to four different forms of magnesium—powder, ribbon, rod, and turnings—in order to answer the question "Qualitatively, how does the form of magnesium affect the rate of its reaction with HCl(aq)?" Students pool their data in order to answer the question. Pairs of students select at least two forms of magnesium in two different amounts. The students execute the experiment and then work in groups of three or four to answer subsequent "thinking about the data" (TATD) questions. They enter their rates in a common spreadsheet available to the entire class; results for one class of students are shown in Table 1. Box 3 gives TATD questions with typical student answers.

The results in Table 1 motivate rich discussions framed by the questions in Box 3. Students discuss and answer the questions as class results are posted and before leaving the laboratory. The results differ from what would be given in a textbook description of the initial rates method focused on the moles of a reactant.

Box 2. Used To Collect Data for Each Experiment Cycle

General protocol (Read entire protocol before starting the experiment.)

1. The following protocol will be used for all kinetics measurements in this lab. The pressure of hydrogen gas will be used to monitor the reaction progress. Use this protocol with a sample of magnesium and a volume of HCl(aq) that you think is sufficient to completely react with magnesium sample. Be sure to wear safety goggles while doing the experiment.
2. Obtain a sample of magnesium, and record any appropriate measurements for the sample.
3. Obtain a sample of hydrochloric acid, make any necessary dilutions, and record the concentration of hydrogen ion.
4. Choose a flask or test tube that can accommodate the stopper for the gas pressure sensor, and place the magnesium in the flask such that it can be completely covered by the HCl solution. For example, magnesium ribbon must be weighted by a loop of copper wire.
5. Place the flask or test tube with the Mg and a separate flask containing the volume of HCl solution for the trial into the water bath to equilibrate. Record the temperature of the water bath.
6. Begin monitoring pressure as a function of time and do so for at least 1 min before starting the reaction.
7. Quickly add the HCl solution to the flask or test tube containing the magnesium, and immediately stopper the flask. You must hold the stopper in place while continuously swirling the flask as the reaction proceeds so that no gas escapes.
8. When the reaction is complete or has slowed significantly, stop the data collection, remove the flask from the bath, and use the stopcock to carefully release the pressure in the flask. The reaction products must be disposed of appropriately.
9. Multiple runs should be made for each set of reaction conditions to ensure reproducibility. (At least two runs must be reproducible to within 10%.)

Table 1. Sample Data for a Class of 16 Students Working in Pairs

Form of Mg	Mass (g)	Rate (kPa/s)
Powder	0.0753	1.82
	0.1508	3.38
	0.0789	2.66
	0.1492	5.76
Ribbon	0.0789	0.364
	0.1509	0.707
	0.0766	0.238
	0.1528	0.380
Rod	7.8406	0.684
	14.9609	1.20
	5.1517	0.504
	11.8251	1.26
Turnings	0.0782	0.117
	0.1534	0.212

For example, doubling the mass of the magnesium powder, ribbon, rod, or turnings results in rate increases ranging from 1.6 to 2.2. The instructor can focus students on possible sources of discrepancies among the groups' results. For example, the powder form of magnesium is prone to clumping, so it is important that the reaction vessel be swirled vigorously during the reaction. It is more important, however, that students begin to recognize that real trends are present in the data. In general, doubling the mass of magnesium doubles the reaction rate for a specific form of magnesium. Closer examination of the results shows that the surface area, not the mass, of magnesium is the parameter controlling the reaction rate.

TATD 6 provokes a vigorous debate among students. Students often select forms other than ribbon as the most appropriate form to determine the reaction rate for various reasons. Some select powder or turnings because those forms react faster. Some select the rod because it reacts the slowest. Usually at least one or two students pick magnesium ribbon due to the ease with which its surface area can be measured. The instructor then leads a discussion about choosing the form for which the surface area can be measured and controlled. At this point, students converge on the ribbon as the most appropriate form with which to continue determining the rate equation.

Discussion between the instructor and the class is vital to ensure that students are guided to the correct choices in developing the next step in each experiment. As with any POGIL activity, without guidance students may come to an incorrect conclusion regarding their next step. We have found that it is essential that discussions about the data take place during "lab time" with instructor guidance.

Only after considering the reaction kinetics qualitatively do students apply quantitative models to data collection and analysis in the second experiment cycle. The rate law equation is introduced. Students develop the ideas needed to study the reaction kinetics using the initial rates method (see Box 4). They also work on the more general process skills of linearizing functions and fitting equations to data to obtain physical parameters.

The students carry out the protocol a second time to determine the rate law parameters. As a class they select a set of hydrogen ion concentrations and lengths of magnesium ribbon to use, dividing up the experiments among different students. Students consult with the instructor regarding their experimental design. Students must consider factors such as the reaction speed and the absolute quantity of hydrogen gas produced. If the reaction is too slow, the rate will be difficult to measure; too fast a reaction (or too much hydrogen) leads to overpressuring of the reaction vessel. Likewise, students need to pick a set of concentrations and ribbon lengths that will provide at least three points for each graph of the linearized rate law equation. Group and class discussions about these factors are quite illuminating. Table 2 shows a class set of data for this experiment.

Working through the next TATD questions, the students graph the appropriate data and determine the reaction orders (Figure 2) and the rate constant. Using hydrogen ion concentrations between 0.2 and 0.5 M, students determine the orders to be approximately 1 for both hydrogen ion and magnesium, which is consistent with a comprehensive study[13] of metal corrosion. (If students select higher concentrations of hydrogen ion, the hydrogen ion order is generally greater than 1 but never above 1.5.)

Students then discuss a third set of experiment preparation questions prior to answering "How does temperature affect rate?" and design the experiments needed to answer this question. The pre-experiment questions ask students to predict the effect of increasing temperature on a reaction rate, to linearize the Arrhenius equation, and to determine which data must be collected to determine the reaction's activation energy.

The experiment ends with application questions similar to those found in most lab textbook experiments. The questions

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Box 3. TATD Questions for Cycle One with Typical Student Responses

TATD Question	Typical Student Responses
1. After each trial, you have a graph of pressure versus time. What parameter is determined from the slope of this graph at short times? (What time frame is appropriate for "short time"?)	Students recognize that the slope of this graph is the rate of the reaction.
2. Why is this method called the *initial rates method* for the determination of kinetics parameters?	Students observe that the rate tends to fall off at long times, and they discuss (or are led to discuss) that the reactants are being used up as the reaction proceeds, thereby slowing the reaction.
3. Qualitatively, how can this slope be used to determine the effect of the magnesium on the reaction rate?	Students recognize that increasing magnesium increases the rate.
4. Determine the slope of the pressure versus time curve for each trial, and report your results in a shared spreadsheet. As a class, review the tabulated data. Write a statement to express the effect of magnesium on the reaction rate. Write this statement in your lab notebook and on the board. Each person in class should be able to verbalize this statement without reading it.	Example student results for the rates are given in Table 2. Students quickly verify quantitatively that increasing the amount of magnesium increases the rate.
5. Which measurable property of magnesium determines the reaction rate? Explain your reasoning. (The class should come to a consensus.)	Most classes have a lengthy discussion about the mass of Mg versus the surface area of Mg controlling the rate of the reaction. Students are guided to use the results of Table 2 to support the statement that the surface area of Mg determines the rate.
6. Which form of magnesium is most appropriate for measuring the property identified in TATD 5?	Discussion of this question is also lengthy; some students argue that powder (or even turnings) is the best form because the reaction is fastest. The instructor can guide the students toward a discussion of how best to both *measure* and *control* the surface area, leading the students to select ribbon as the best form.

Box 4. Experiment Preparation Questions for the Second Experiment Cycle

7. What is varied to determine the order of the reaction with respect to the magnesium? What is varied to determine the order of the reaction with respect to hydrogen ion? What is not varied in each determination? What parameters in this equation are constants?	Students are presented with the rate law, $\text{rate} = \left(\frac{dP_{H_2}}{dt}\right) = kS_{Mg}^{a}[H^{+}]^{b}$ in the text before this question. Students are led to discuss the constants and often realize based on their discussions that the rate constant is temperature dependent.
8. Take the logarithm of both sides of the rate law equation. Show how *a* and *b* can be determined by a linear least squares fit of rate versus the quantities identified in TATD 7. The class must reach consensus the identity of the independent and dependent variables, the slope, and the intercept.	Students sketch out the planned graphs, noting the variables on the x- and y-axes.
9. What is the minimum number of points needed to establish that a set of data likely falls on a straight line?	This question leads to fruitful discussion about what is required to make an experimentally valid line.

may ask students for real-world applications or to suggest additional, related experiments. Students may be required to derive an equation used in the analysis. Postexperiment questions also ask students to look up and describe relevant peer-reviewed publications. The answers to these questions often form the basis of the discussion section of student reports for POGIL-PCL experiments.

The POGIL-PCL experiment in conjunction with its instructor handbook applies POGIL principles to the physical chemistry laboratory course. The experiments emphasize laboratory process skills such as modeling and experimental design along with the POGIL process skills[14] of critical thinking, problem solving, information processing, and teamwork. The instructor plays a critical role, guiding students to discover and model chemical phenomena in a laboratory setting. These experiments build on the incorporation of guided inquiry as developed by Holy Cross, SWH, and PCOL, adding "data-think" cycles that mimic the nature of scientific research.

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Table 2. Class Set of Data Used To Determine the Rate Law for the Reaction of Mg with HCl(aq)

Reaction Order for S_{Mg}, $[H^+]$ = 0.25 M		Reaction Order for $[H^+]$, S_{Mg} = 1.20 cm^2	
S_{Mg} (cm^2)	rate (kPa/s)	$[H^+]$ (M)	rate (kPa/s)
0.76	0.0131	0.2	0.0120
0.76	0.0187		0.0151
0.60	0.0214		0.0233
0.60	0.0231		0.0298
1.00	0.0381	0.25	0.0381
1.00	0.0332		0.0332
1.40	0.0528		0.0528
1.20	0.0499		0.0499
2.40	0.0724	0.5	0.0815
2.40	0.0813		0.0780
2.40	0.0850		0.0626
0.76	0.0932		0.0622

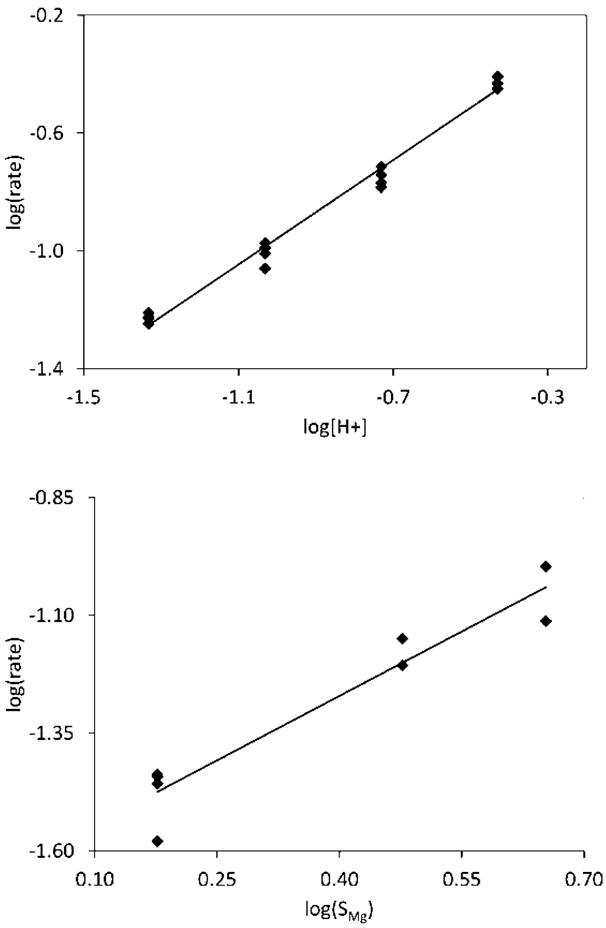

Figure 2. Class results for determination of the reaction order. The orders are 0.89 ± 0.02 (R^2 = 0.99) and 0.9 ± 0.1 (R^2 = 0.9) for the hydrogen ion concentration and surface area of magnesium, respectively.

Assessment of student learning as a result of performing POGIL-PCL experiments is critical and will be the focus of future studies. Although qualitative and preliminary, we observed students doing POGIL-PCL experiments who demonstrated improved conceptual understanding, took ownership of lab decisions, and were more creative and independent in the laboratory. But these gains can come at an expense. We rarely find that a POGIL-PCL experiment can be completed in a single scheduled laboratory period, often requiring six to eight h of in-class laboratory work, discussion, and data analysis. The authors believe this additional time is well worth the gains in student understanding we have observed.

■ POGIL-PCL EXPERIMENTS IN THE INQUIRY-BASED EXPERIMENT CONTEXT

Various authors have evaluated laboratory manuals to determine the extent to which their experiments are inquiry-based. In a review of high school chemistry experiments, Herron[15] found three types of experiments: those for which students observe known phenomena, those for which student observations lead to the discovery of a known model via generalization, and those for which students make observations in order to solve an open-ended problem (qualitative analysis). Pavelich and Abraham[2] similarly proposed three levels of inquiry, labeling them verification, guided inquiry, and open inquiry. They define a guided-inquiry experiment as one in which data is collected before students are led to the development of the concept. More recently, Buck et al.[16] proposed a detailed rubric for the assessment of published chemistry experiments based on which sections (e.g., theory/background, methods/procedure, analysis) of experiments are provided to students. In their rubric a structured-inquiry experiment provides the students with the theory, method, and analysis, but students determine the results and conclusions (outcomes).

Where do POGIL-PCL experiments fall within the verification–guided inquiry–open inquiry framework? POGIL-PCL experiments fit the Pavelich and Abraham definition of guided inquiry and the Buck et al. definition of structured inquiry. Students have limited background information before doing the experiment (aside from prior knowledge), and they do not know the experimental outcome. A generic protocol is provided, but students must make some decisions about the specific procedure based on data collected during the first data-think cycle in the experiment. Likewise, the experiments provide the data analysis framework, but the analysis is presented in a series of guided-inquiry questions. The data-think cycles most closely resemble the apprenticeship model of research. Students carry out a "dry-run" of an experiment under the guidance of an expert in order to determine which experimental parameters are best modified or tested in subsequent runs of the same experiment.

■ CONCLUSION

The POGIL-PCL experiment framework and a number of POGIL-PCL experiments were developed by the authors and a consortium of physical chemistry faculty at a series of two-day workshops. Faculty who have attended the workshops conceptualize, write, review, and test experiments, often collaboratively. This paper describes the POGIL-PCL framework for experiments in the physical chemistry laboratory course using the experiment "What are the kinetic parameters of a heterogeneous reaction?" as an example of an experiment that has been fully reviewed and tested by workshop participants.

Additional POGIL-PCL experiments are at the reviewing and testing stage of development; two are described here as further examples of this project. In one experiment students answer the question "How does the composition of a mixture affect its melting point?" by measuring the freezing temperature of various mixtures of fatty acids and constructing the solid–liquid phase diagram. Along the way, they predict the freezing point of a mixture and eutectic point and the shape of the phase diagram, and they select which mixtures to study. In another experiment, "What factors control the escapability of a molecule from a liquid?", students calculate the macroscopic enthalpy of vaporization from energies obtained by molecular dynamics simulations. The experiment requires students to predict the relative importance of different intermolecular and intramolecular forces for the vaporization process and the relative enthalpies of vaporization for pentane isomers.[17]

An additional goal of the POGIL-PCL project is to create a sustainable community of physical chemistry lab instructors, both to work on the development and implementation of experiments and to provide connections among faculty who are often the only physical chemist at their institutions. Over 50 faculty have attended one or more of these workshops. We have also written a rubric specific to POGIL-PCL for assessing these experiments that was used to evaluate experiments in the development pipeline. The rubric asks reviewers to decide if a particular POGIL-PCL experiment element is present or absent. A subsequent paper will describe the rubric, the review process, and these workshops in detail. Further papers from the authors and workshop participants will describe specific POGIL-PCL experiments that were initiated at these workshops and tested and implemented under the POGIL-PCL umbrella.

■ ASSOCIATED CONTENT

Supporting Information

Instructor handbook; student handouts. This material is available via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) Committee on Professional Training. *Undergraduate Professional Education in Chemistry: ACS Guidelines and Evaluation Procedures for Bachelor's Degree Programs Physical Chemistry Supplement*; American Chemical Society: Washington, DC, Spring 2008.

(2) Pavelich, M. J.; Abraham, M. A. An Inquiry Format Laboratory Program for General Chemistry. *J. Chem. Educ.* **1979**, *56*, 100−103.

(3) Allen, J. B.; Barker, L. N.; Ramsden, J. H. Guided Inquiry Laboratory. *J. Chem. Educ.* **1986**, *63*, 533−534 and references therein..

(4) Halpern, A. M.; McBane, G. C. *Experimental Physical Chemistry*, 3rd ed.; Freeman: New York, 2006.

(5) Garland, C. W.; Nibler, J. W.; Shoemaker, D. P. *Experiments in Physical Chemistry*, 8th ed.; McGraw-Hill: New York, 2009.

(6) Abrash, S. A. Modern Developments in the Physical Chemistry Laboratory. In *Advances in Teaching Physical Chemistry*; Ellison, M. D., Schoolcraft, T. A., Eds.; ACS Symposium Series; American Chemical Society: Washington, DC, 2007; Vol. 973, Chapter 8, pp 115−151.

(7) Greenbowe, T. J.; Burke, K. A. Instruction By Using the Writing Heuristic. In *Science Inquiry, Argument, and Language: A Case for the Science Writing Heuristic*; Hand, B. M., Ed.; Sense Publishers: Rotterdam, 2007. Burke, K. A.; Greenbowe, T. *Science Writing Heuristic Web*, http://avogadro.chem.iastate.edu/SWH/homepage.htm (accessed Oct 2014).

(8) Deckert, A. A.; Nestor, L. P.; DiLullo, D. An Example of a Guided-Inquiry, Collaborative Physical Chemistry Laboratory Course. *J. Chem. Educ.* **1998**, *75*, 860−863.

(9) Whisnant, D.; Sauder, D.; Zielinski, T. J.; Towns, M. Physical Chemistry On Line: Interinstitutional Collaboration at a Distance. *J. Chem. Educ.* **2001**, *78*, 414.

(10) Lamba, R. S.; Creegan, F. J. The Process-Oriented Guided Inquiry (Discovery) Laboratory. In *Process-Oriented Guided Inquiry Learning (POGIL)*; Moog, R. S., Spencer, J. N., Eds.; ACS Symposium Series; American Chemical Society: Washington, DC, 2008; Vol. *994*, Chapter 16, pp 186−199.

(11) Abraham, M. R. Inquiry and the Learning Cycle Approach. In *Chemists' Guide to Effective Teaching*; Pienta, N. J., Cooper, M. M., Greenbowe, T. J., Eds.; Pearson Prentice Hall: Upper Saddle River, NJ, 2005; Chapter 4.

(12) Birks, J. P.; Walters, D. L. Pressure Measurements to Determine the Rate Law of the Magnesium-Hydrochloric Acid Reaction. *J. Chem. Educ.* **1993**, *70*, 587−598.

(13) Hibashi, F. Kinetics of Corrosion of Metals. *J. Chem. Educ.* **1965**, *42*, 318−322.

(14) Moog, R. S.; Spencer, J. N. POGIL: An Overview. In *Process Oriented Guided Inquiry Learning (POGIL)*; ACS Symposium Series; American Chemical Society: Washington, DC, 2008; Vol. *994*, Chapter 1, pp 1−13.

(15) Herron, M. D. Nature of Scientific Inquiry. *Sch. Rev.* **1971**, *79*, 171−212.

(16) Buck, L. B.; Lowery Bretz, S.; Towns, M. H. Characterizing the Level of Inquiry in the Undergraduate Laboratory. *J. Coll. Sci. Teach.* **2008**, 52−58.

(17) Reeves, M. S.; Whitnell, R. M. New Computational Physical Chemistry Experiments: Using POGIL Techniques with Ab Initio and Molecular Dynamics Calculations. In *Addressing the Millennial Student: New Pedagogy and Approaches to Improve Student Learning Outcomes in Undergraduate Chemistry*; ACS Symposium Series; American Chemical Society: Washington DC, in press.