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Supporting Engagement in Metamodeling Ideas in General Chemistry: Development and Validation of Activities Designed Using Process Oriented Guided Inquiry Learning Criteria

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ABSTRACT: Metamodeling ideas move beyond using a model to solve a problem to consider the nature and purpose of a model, such as reasoning about a model's empirical basis and understanding why and how a model might change or be replaced. Given that chemistry relies heavily on the use of models to describe particulate-level phenomena, developing sophisticated ideas about models reflects a critical competency for undergraduate students in chemistry courses. Here we describe a set of collaborative learning activities developed using the design criteria for process oriented guided inquiry learning. The activities were designed to use general chemistry topics as a context to engage students in the metamodeling ideas: model changeability, model multiplicity, evaluation of models, and process of modeling. In addition to learning relevant content (gas laws, nuclear chemistry, orbitals, colligative properties, equilibrium, chemical kinetics), each activity provides opportunities to reason about the nature of models, including mathematical models such as equations and graphs. As a practical consideration, the complete activities and instructor guides are provided as editable files.

KEYWORDS: *General Public, First-Year Undergraduate/General, Collaborative/Cooperative Learning, Inquiry-Based/Discovery Learning, Learning Theories, Gases, Equilibrium, Quantum Chemistry, Physical Properties, Kinetics*

In typical chemistry instruction students are provided opportunities to use models such as equations to solve problems—prompting students to think *with* models—but they are less often expected to consider the nature of models, such as the role of data in their development and revision—prompting students to think *about* models.[1] Knowledge associated with thinking *about* models has been described in the literature as metamodeling knowledge,[2] reflecting epistemological assumptions regarding the nature and purpose of models. Developing sophisticated metamodeling ideas is important because of the abstract nature of chemistry, in which the chemistry curriculum can be viewed as the presentation of a series of models of increasing complexity.[3] Research on students' understanding of models indicates that although students have productive metamodeling ideas regarding the nature and purpose of models, they are less likely to apply these ideas to mathematical models such as graphs and equations.[4]

In order to help support students in the engagement of metamodeling ideas, our research group has developed a set of collaborative learning activities using the design criteria for process oriented guided inquiry learning (POGIL).[5] General chemistry topics were selected as the context for students to develop metamodeling ideas, with an emphasis on reasoning *about* mathematical models, including gas laws, nuclear chemistry, orbitals, colligative properties, equilibrium, and chemical kinetics. Given that metamodeling ideas reflect epistemological assumptions, our goal with the activities is not to directly address metamodeling ideas by introducing additional terminology to students (e.g., *model changeability*). Instead, we focus on eliciting engagement in metamodeling ideas by providing students rich opportunities; for example, a question that requires students to consider why a model may need to be revised. This is a subtle, but important, distinction, because the intention is not to introduce additional content learning objectives but to focus on ways to engage students in science practices (i.e., process skills) as they learn the content. In this contribution, we provide an overview of the activities and describe their development, which involved multiple stages of refinement and validation. We have also provided as supplemental files the complete activities, along with instructor guides.

METAMODELING

Extant literature describes metamodeling knowledge as comprised of several dimensions that emphasize the nature and purpose of models.[6−16] In our earlier work, we developed a series of construct maps, representing progressions in the ways that students think about four metamodeling constructs.[17] We have drawn on this work and have incorporated learning objectives related to these four dimensions of metamodeling knowledge into the activities described in the

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present manuscript. Below, we discuss the four dimensions of model changeability, model multiplicity, evaluation of models, and the process of modeling as they are described in our earlier work and other literature. We also provide examples of the relevance of this type of knowledge for chemistry students.

Dimensions of Metamodeling Knowledge

Model changeability refers to the idea that models may change as part of normal scientific activity. Because models are scientist-constructed tools whose value is derived from their explanatory and predictive utility, models may be altered or replaced in light of new evidence or interpretations of that evidence.[6,9,10,15−17] For example, the assumption that mass is conserved in chemical equations is a productive assumption, but when nuclear reactions are under consideration, a different description that encompasses the interchangeability of energy and mass must be used.

Model multiplicity refers to the notion that scientists often use multiple models to explain and/or predict a single phenomenon. Often different models may be used to emphasize different features of the target phenomenon, or additionally, multiple models can represent alternative sets of assumptions and limitations of the models.[6,9,10,13,15−17] This is the case for the use of multiple mathematical models in predicting gas behavior. The ideal gas law equation is commonly used in general chemistry for predicting gas behavior under given conditions; however, the van der Waals equation may be used for the same purpose and can be used when the assumptions of kinetic molecular theory are not met.

Evaluation of models refers to the idea that a model's quality may be assessed according to its scientific utility, such as the explanatory power of the model or accuracy of the predictions made using the model.[6,9,10,13,15,17] Models may also be evaluated according to communicative criteria such as interpretability.[18] When evaluating models, different types of data or representations of the same data could be compared in order to consider the extent in which agreement is observed. As an example, an orbital diagram should be consistent with the data presented in a radial distribution plot.

Finally, the process of modeling refers to the idea that models are developed by scientists and are often based on observed patterns in data. The process of modeling may be iterative and include both the evaluation of models and changing models according to new findings.[6,15−17] The construction and refinement of scientific models is a creative process and requires consideration of relevant variables and assumptions. As an example, discussion of chemical kinetics in general chemistry provides an opportunity for students to engage in the process of constructing mathematical models (rate laws) from empirical data (initial rates).

■ PROCESS ORIENTED GUIDED INQUIRY LEARNING

Overview

As indicated in a metaanalysis of active learning, instruction that is more student-centered results in better performance outcomes for students,[19,20] a finding that is echoed in a meta-analysis that focused specifically on the active learning approach process-oriented, guided-inquiry learning.[21] Initially developed in the chemistry community,[22] POGIL is a content-neutral pedagogical approach[23,24] that emphasizes the social construction of knowledge through student-directed group work.[25] A central feature of POGIL activities is the learning cycle, involving an exploration phase, a concept invention phase, and an application phase.[22,26] From a theoretical perspective, these phases in the learning cycle map onto Piaget's work related to developmental psychology, describing stages of assimilation, accommodation, and organization.[27−29] In the first phase of the learning cycle, students *explore* as they are provided a model—which could be a diagram, text, graph, or equation—and are prompted with direct questions to make inferences. For the second stage of the learning cycle, students engage in *concept invention* as they develop a formal definition for an idea based on their observations. In the final stage of the learning cycle, students engage in the *application* of the new concept they just developed, in which they are prompted to utilize the idea in a new context. During a typical POGIL activity, students move through multiple learning cycles during class time, which is intended to replace formal instruction about a topic. The broad applicability of POGIL as an instructional approach is illustrated in its implementation beyond science disciplines, to fields such as aviation,[30] finance and marketing,[31,32] and foreign languages.[33]

Process Skills

With respect to designing POGIL activities, the POGIL Project has developed resources that include information about the general format of POGIL activities.[5] These resources include suggestions regarding framing questions in the learning cycle (called "Critical Thinking Questions"), outlining requirements for the inclusion of additional questions for students to practice the content outside of class ("Exercises", simple questions that are similar to questions discussed in the learning cycle; "Problems", more complex questions that require students to make inferences and draw connections), and stating that POGIL activities must have clearly articulated goals for both content and process skills. As implied by its name, process oriented guided inquiry learning emphasizes the development of *process skills*, such as critical thinking and problem solving,[22] with the POGIL Project emphasizing the importance of not only having content learning objectives for an activity but also explicitly articulating goals for process skills.[5] We argue that process skills are closely aligned with what has been described as science practices. Science practices can be defined as the "disaggregated components of inquiry" that scientists use to solve problems and answer questions.[34] According to the *Framework for K−12 Science Education*,[35] science practices encompass the following skills: asking questions; developing and using models; planning investigations; analyzing and interpreting data; using mathematics and computations thinking; constructing explanations; engaging in argument from evidence; and obtaining, evaluating, and communicating information. The utility of reframing skills such as critical thinking using the language of science practices has previously been discussed in the literature, with the main advantage being the clearly defined nature of science practices.[36] Moreover, given there is a national movement toward emphasizing science practices in K−12 and at the university level,[37−39] resources for incorporating science practices in instruction are available and continue to be developed.[40−43] Therefore, when considering how to promote the development of process skills, activity development was informed by literature related to science practices. In particular, for the current work, we are interested in the science practice *developing and using models*, which incorporates thinking *with* and *about* models.[1]

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Table 1. Process Skill Goals for Each Activity

Metamodeling Dimension	Activity	Process Skill Goals—Students Can:
Model Changeability and Model Multiplicity	Gas Laws	Use a simulation to identify the relationship among the variables of pressure, volume, moles, and temperature to construct the ideal gas law
		Use a simulation to identify assumptions and limitations of the ideal gas law and identify the need for model revision
	Nuclear Chemistry	Construct a model related to the conservation of mass based on patterns observed in data
		Identify the need for model revision based on additional information and observations
Evaluation of Models	Orbitals	Evaluate claims made using models
		Recognize the predictive power of probability-based models
	Colligative Properties	Use data to draw conclusions
		Evaluate the validity of predictions against data
Process of Modeling	Equilibrium	Identify relationships based on empirical data
		Use graphical representations of data to draw conclusions
	Chemical Kinetics	Design an approach for determining the rate law based on patterns observed in empirical data
		Use graphical representations of data to draw conclusions

■ VALIDATION AND REVISION

The development of the collaborative learning activities was an iterative process involving cycles of obtaining feedback followed by revision. In the first stage of development, the activities were designed using POGIL design criteria with an emphasis on metamodeling ideas, and then they were piloted with our research group, which is comprised of multiple graduate and undergraduate students. During this stage of development our research group worked through the activities in a way analogous to how undergraduates would work through the activities (working in groups of 3 or 4, assigning POGIL roles, etc.). This was followed by a debriefing session where suggestions were made to improve the activities. After modifying the activities based on the group's feedback, in the second stage of development, content validation was performed with six chemistry faculty who are familiar with POGIL and are part of the POGIL community. Each chemistry faculty reviewed two activities, with each activity being reviewed by two different faculty. Based on discussions with the chemistry faculty, additional changes were made to the activities to modify the wording and framing of questions.

For the third stage of development, we conducted interviews with undergraduate students. All data was collected in accordance with our Institutional Review Board, including communicating to students that participation was voluntary and had no impact on their grade. As compensation for their time, students received a $20 gift card. The undergraduate students were recruited from a general chemistry course for STEM majors, and interviews were aimed at establishing response process validity to ensure students were interpreting the activities as intended.[44] Three students were interviewed for each activity (n = 18). After interviewing the students, the activities underwent additional revision.

In the final stage of activity development, each activity (except for the orbitals activity) was implemented in two discussion sections, with each discussion section containing roughly 24 students and lasting 50 min. As part of this implementation, we collected audio and video data, and a researcher took observation notes as students worked in groups. Moreover, for the activities implemented in the discussion classrooms, teaching assistants received informal training regarding facilitation of the activities including how to utilize assigned roles. In the case of the orbitals activity, we were unable to collect classroom observation data; however, we did three clinical group interviews (3−4 students) for three of the activities (gas laws, nuclear chemistry, orbitals), with the goal of investigating features of collaborative learning (e.g., process skills, student roles, learning cycle structure, etc.). We elected to use video and audio data from the three clinical group interviews for the orbital activity since we were unable to collect classroom observation data. As before, changes (albeit minor changes at this stage) were made to each activity following data collection.

The activities included in the Supporting Information section are the final version of the activities that resulted from our multiple-stage development process. We also created companion instructor guides that provide an answer key and provide insight regarding how to support students as they work through the activities based on the data collected for each stage.

■ OVERVIEW OF ACTIVITIES

As part of designing the activities around metamodeling constructs and POGIL design criteria, we utilized considerations related to evidence-centered design, which involved identifying the type of knowledge, skills, and abilities we wanted students to develop and considering the evidence that could be used to demonstrate these goals were met.[45] In practice, the aim was that each activity would involve engagement in at least one metamodeling dimension, with all of the metamodeling ideas reflected as a set among the activities designed. That said, in addition to having content learning objectives for each activity, we also have process skill goals for each activity, with at least one process skill goal for each activity emphasizing *developing and using models* by providing an opportunity for students to engage in metamodeling ideas. We have provided the specific process skills goals for each activity in Table 1.

Using general chemistry content as the context for students to engage in metamodeling ideas, we designed six collaborative learning activities. For each activity, students work through two POGIL learning cycles (about 50 min in total) to develop chemistry principles while simultaneously using mathematical models to engage in model changeability, model multiplicity, evaluation of models, and the process of modeling. In the section that follows, an overview of the activities is provided, organized based on the target metamodeling construct. For each activity, a brief discussion of previous research related to

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the relevant topic is presented, followed by a description of how the activities complement existing published POGIL materials,[46,47] along with a summary of the content and metamodeling ideas discussed in the activity. We also provide a question from each activity and student data collected to illustrate student engagement in metamodeling ideas. The complete activities, including an instructor guide containing an answer key with suggestions for implementation, are provided as files in the Supporting Information section.

Model Changeability and Model Multiplicity

As stated previously, *model changeability* refers to the idea that models change during the scientific process, and closely related, *model multiplicity* refers to the idea that different models may be used by scientists depending on the context. Both metamodeling ideas emphasize that different models or versions of models exist (over time or simultaneously), and based on the overlap between these metamodeling constructs, we decided to combine them and target them in the context of gas laws and nuclear chemistry. These activities involve engagement in model multiplicity and model changeability as students identify the need to use a different model and modify their current model (e.g., ideal gas law, law of conservation of mass) to account for new observations regarding the limitations of the model

Gas Laws: Using a Dynamic Computer Simulation to Construct the Ideal Gas Law

Research into students' reasoning related to the ideal gas law has primarily focused on students' problem solving, indicating students perform better when questions are framed algorithmically instead of conceptually.[48−55] Other work detailed the common features of gas law problems that tended to lead students to incorrect answers more often, such as number format (i.e., scientific, general, decimal) and unit conversions for variables.[56] Building on this literature, Tang and Pienta[57] divided gas law problems into three stages, problem reading, problem planning, and calculation, noting that unsuccessful students spent more time in the planning phase while successful and unsuccessful students spent the same time in the reading phase, suggesting students need more explicit scaffolding regarding how to approach problems. In previously published POGIL activities related to gas laws,[46,47] students are provided the ideal gas law equation and prompted to indicate relationships between variables, accompanied by a similar approach for related equations (e.g., Boyle's Law). In our activity, during the first learning cycle students use a dynamic computer simulation to make observations regarding the relationships between variables (P, V, n, T) in order to construct the ideal gas law. In the second learning cycle students use the interactive simulation to identify limitations in the equation and posit how the equation could be changed to account for these limitations.

An example question from this activity is provided in Figure 1, in which students are prompted to recognize that the assumptions for the ideal gas law do not always work. In the response provided, the students were able to use the simulation to draw inferences about the limitations of the ideal gas law, noticing that at low temperatures the particles are more attracted to one another, which is less of an issue at high temperatures. This question is foundational in order for students to recognize the need for a different model (i.e., model multiplicity). Later in the activity, students are prompted to focus on the variables in the ideal gas law and

Sample Question

Under what conditions for temperature will these new variables (e.g., particle attraction) have more of an effect: High temperature or low temperature?
(Circle one, explain your reasoning.)

Student Responses

Florence:	[After using the simulation] "Oh, so the particles are more attracted."
Penny:	"At lower temperatures."
Chloe:	"Yeah."
Macy:	"So, it would be low temperature?"
Florence:	"Yeah."
Interviewer:	"And why low temperature?"
Florence:	"Because they're more attracted to each other and they're not, like if it was constant temperature and the constant particle attraction, it would be most similar to the high temperature, high particle attraction."
Interviewer:	"And why do you think at a high temperature it doesn't matter much?"
Florence:	"Because particles are moving faster."

Figure 1. Example question from the Gas Law Activity.

consider how they need to be modified in order to account for the assumptions of the ideal gas law (i.e., model changeability), alluding to the van der Waals equation; for example, considering whether the actual measured pressure (P_{real}) is larger or smaller than expected (P_{ideal}).

Nuclear Chemistry: What Happens to the "Extra" Mass?

Generally, the focus of research for effectively teaching nuclear chemistry has been primarily in secondary education environments,[58,59] with limited literature on the development of nuclear chemistry concepts for students in higher education. Although nuclear chemistry in an undergraduate setting has not been the main focus of educational studies, research indicates it is a topic that initiates natural curiosity in students due to its complexity and significance.[60] Previous general chemistry POGIL activities related to nuclear chemistry focus on calculating binding energy and balancing nuclear reactions given different types of radioactive decay.[46] For our activity, emphasis is placed on foundational principles, such as the conservation of mass and energy. During the first learning cycle, students use tables with balanced reactions and molar mass values to compare the mass of products and reactants in order to draw conclusions regarding the conservation of mass (Figure 2). For the second learning cycle, students perform similar calculations with nuclear reactions and are prompted to revisit their conception of mass conservation to include energy.

As shown in Figure 3, one of the questions from the nuclear chemistry activity asks students to consider their previous observations regarding the conservation of mass, with the goal of getting students to recognize the relationship between mass and energy. Based on their observations with chemical reactions, the students in Figure 3 (and other groups in our data set) stated a variation of the phrase *mass is not created or destroyed*. Then, after being presented with data related to nuclear reactions, they recognized their previous statement regarding mass conservation does not apply. After brainstorming possible reasons why there is a mass discrepancy between products and reactants (e.g., high energy particles, other groups suggested inaccurate data was provided), the students constructed an explanation that involved the conversion of mass into energy. This illustrates students modifying their

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Nuclear Chemistry: Reaction Heat and Molar Mass Data

Reaction	Energy Released, J/mol
$2C_8H_{18} + 25O_2 \rightarrow 16CO_2 + 18H_2O$	5.47×10^6
$S + O_2 \rightarrow SO_2$	2.96×10^5
$2Al + Fe_2O_3 \rightarrow Al_2O_3 + 2Fe$	8.50×10^5
$^{236}U \rightarrow {}^{92}Kr + {}^{141}Ba + 3\,{}^{1}n$	1.62×10^{13}
$^{212}Po \rightarrow {}^{208}Pb + {}^{4}He$	9.00×10^{11}

Particle	Molar Mass, g/mol
Neutron (n)	1.01
Hydrogen-1	1.01
Helium-4	4.00
Carbon-12	12.00
Nitrogen-14	14.00
Oxygen-16	15.99
Sulfur-32	31.97
Krypton-92	91.93
Barium-141	140.91
Lead-208	207.98
Polonium-212	211.99
Uranium-236	236.05

Figure 2. Example model used for the Nuclear Chemistry Activity.

Sample Question

Update your assertion in Question 4 related to mass conservation to reflect your additional observations about reactions. In particular, consider $E = mc^2$.

Student Responses

Preston: "Kind of going back to the last one, but do you think it's just like getting at that the mass that is like destroyed is then electrons, because electrons are super light and if like energy is given off, electrons are emitted in light. So, that's why I'm wondering if it's electrons. I don't know if that's necessary for when we go forward, but it might be helpful to keep in mind."

Maggie: "It could be. I mean if it's going fast enough like yeah, anything has a lot of energy. [re-reads question] … So, I think it's what we just discussed is that the more mass there is, the more energy there … because light, the speed of light is a constant. So, the more mass that is going at the speed of light, means more energy."

Riley: "So, should I say like the more mass that is like, not like lost during the reactions, but."

Maggie: "Converted."

Riley: "Okay."

Preston: "… So, we have that the more mass that is conserved or sorry, converted during the reaction, the more energy is given off. Converted, meaning the mass is converted into energy."

Figure 3. Example question from the Nuclear Chemistry Activity.

previous model (model changeability) in favor of a new model that applied for nuclear reactions (model multiplicity).

Evaluation of Models

In the case of the metamodeling idea *evaluation of models*, an emphasis is placed on assessing a model based on metrics such as its agreement with data or general utility. For the activities we designed, we focused on orbitals and colligative properties as opportunities for students to evaluate how models relate to provided data. These activities involve engagement in the evaluation of models, as students identify trends and evaluate claims related to data provided (e.g., orbitals and radial distribution plots, trends related to vapor pressure and boiling point).

Orbitals: Cloudy with a Chance of Electrons

Prior research indicates that difficulties arise when students are asked to relate probability, electron location, and other ideas related to quantum mechanics.[61−63] The literature additionally suggests that students tend to use quantum models to describe classical phenomena and utilize language that is not productive for understanding orbitals.[64−68] Published POGIL activities related to orbitals have emphasized quantum numbers and discussed hybrid orbitals in relation to bonding.[46] For our activity, we focus on emphasizing the idea of probability and its relation to orbitals. During the first learning cycle of our activity students are prompted to discuss probability in a familiar context, reasoning about *chance of rain* and the associated variables with the probability of precipitation model. For the second learning cycle, students identify the parameters associated with the probability-based model of an atom by drawing connections to their previous discussion related to the probability of precipitation model. Because the Schrödinger Equation allows us to analyze the construction of orbitals through the input of values, students are then guided to recognize the information provided by the Schrödinger Equation and are guided to draw inferences about orbital diagrams and their relationship to radial distribution plots. Although the Schrödinger Equation draws on calculus-based concepts, students are not required to have any prior knowledge of calculus to complete this activity (Figure 4).

In a general sense, the framing of the activity with the *chance of rain* discussion was intended to support students by having them consider an accessible context involving probability, which could then be used as an entry point for a discussion of more complex phenomena involving probability, such as orbitals. For example, in one of the questions from the orbitals activity (Figure 5), students are prompted to evaluate a probabilistic claim related to the location of an electron in an orbital (i.e., evaluation of models). For this question, students typically responded by acknowledging the nature of probabilistic phenomena, which involve multiple possible outcomes. In the case of the students below, they drew a connection between the probability of rain discussion from earlier in the activity, recognizing the claim provided is not "correct" or "incorrect".

Colligative Properties: Analyzing Patterns and Trends Related to Vapor Pressure and Boiling Point

Colligative properties, including vapor pressure, freezing point depression, boiling point elevation, molality, and osmotic pressure, are not focused on in the present literature, with a lack of research and educational tools and activities related to these concepts.[79] The few published activities on colligative properties that are available for undergraduates were created for laboratory settings and analyze concepts like freezing point depression and vapor pressure.[69,70] In previously published POGIL activities related to colligative properties, students are provided equations related to boiling point elevation/freezing point depression and asked to perform calculations and draw

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Orbitals: Schrödinger Equation

Provided below is the Schrödinger equation. Solving the Schrödinger equation yields the wavefunction (Ψ), a mathematical equation that describes information about an electron in an atom. One way to think of the wavefunction is as a tool that provides an output given an input, in which the output information is probabilistic in nature, here represented by an orbital.

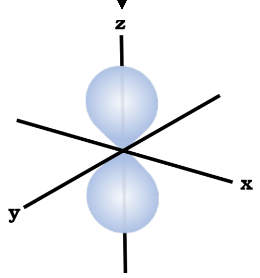
Values for relevant parameters

↓ Input

Schrödinger Equation

$$-\frac{\hbar^2}{2m}\left(\frac{\partial^2\Psi}{\partial x^2}+\frac{\partial^2\Psi}{\partial y^2}+\frac{\partial^2\Psi}{\partial z^2}\right)+U(x,y,z)\Psi(x,y,z)=E\Psi(x,y,z)$$

↓ Output



Orbital

Figure 4. Example model used for the Orbitals: Schrödinger Equation Activity.

Sample Questions

Suppose that your instructor said there was a 90% probability of finding the electron "within" the orbital and, in fact, after collecting data it turns out the electron is not there. What would you conclude about the statement that there was a 90% chance of finding the electron "within" the orbital? Is the statement correct or incorrect? Why or why not?

Student Responses

Pia: "What would you conclude about the statement that there was a 90% chance of finding the electron within the orbital?"

Madi: "I think that's like the one where like the 20% chance that it's gonna rain and it didn't. Where like there's always, you're never going to be for sure, and like, you know, maybe."

Pia: "I don't know. I think that just says that the model isn't completely accurate, like it has a percent error with it. And it doesn't mean that like the 90% chance statement is incorrect. Cause like there's always, if they say 90%, there's the 10% that it won't, and unless you said a hundred, then that statement is not incorrect."

Fiona: "So, since you didn't say a hundred, you can't be correct or incorrect."

Pia: "Right. It's like, it's not incorrect, but it, you can say it's not necessarily trustworthy, you know what I'm saying?"

Figure 5. Example questions from the Orbitals Activity.

conclusions.[46] For our activity, emphasis was placed on guiding students to construct a definition for vapor pressure and colligative properties, along with recognizing that vapor pressure is a colligative property. In the first learning cycle, students are provided a particulate representation (Figure 6) and students are guided to develop a conceptual understanding

Colligative Properties: Phase Equilibria Particulate Representation

Three different pure compounds (liquids) are poured into sealed containers under vacuum. Initially, the pressure inside each container was zero, but after a brief period of time, the pressure changed for each container. A particulate-level description of this scenario is provided below along with gauges that indicate the final pressure inside each container. Each compound can be represented by the general reaction: Y (l) ⇌ Y (g)

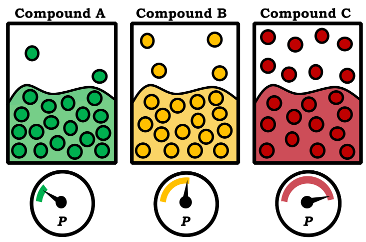
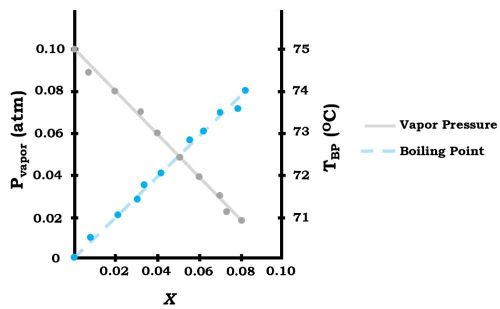


Figure 6. Example model used for the Colligative Properties Activity.

of vapor pressure. During the second learning cycle, students are provided graphical representations (Figure 7) and are prompted to draw conclusions regarding the addition of solute and its influence on vapor pressure.

Sample Questions

For vapor pressure, is this data consistent with the previous data presented? Why or why not? How does this data compare with your prediction regarding boiling point?



Student Responses

Amber: "So, it's proportional with, like the one, the vapor pressure, like going down as you add more, like it's like directly correlated, it's like consistent."

Martha: "Yep."

Peggy: "But, I don't, we didn't have a boiling point. Boiling point goes up as the solute is added, so yeah.

Candice: "So, what do I write?"

Peggy: "... both of them are consistent because as you add more solute the vapor pressure goes down."

Candice: "They're both?"

Peggy: "And as you add more solute the boiling point goes up. Because that's what we said in number 16 [previous question], if you add more, it [boiling point] increases."

Figure 7. Example questions from the Colligative Properties Activity.

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Figure 7 provides example questions from this activity in which students are provided a graph related to vapor pressure and boiling point and students are asked to compare it with data previously presented in the activity. For context, the data students were previously presented were linear graphs depicting partial pressure vs mole fraction of solute, from which students elicited general trends related to vapor pressure and boiling point. Here, students are prompted to engage in the evaluation of models as they assess the extent in which the graphs are consistent with one another (i.e., depict the same trends). In the student response provided, the group reaches a consensus that the data provided is consistent with their previous observations.

Process of Modeling

The final metamodeling construct, *process of modeling*, focuses on the empirical nature of models, emphasizing that scientists construct models based on patterns in data. We utilized equilibrium and chemical kinetics to contextualize this metamodeling idea. These activities involve engagement in the process of modeling as students draw inferences by recognizing patterns in data.

Equilibrium: Developing a Conceptual Definition

In the case of equilibrium, research indicates students often conflate equilibrium and kinetics ideas, such as *rate laws* and *equilibrium expressions* or *rate* and *extent*.[71−75] Multiple POGIL activities have been published that focus on different aspects of equilibrium, including the equilibrium expression, reaction quotient, and solubility product.[46,47] During these activities students are told from the beginning that reactions can be reversible using the double-arrow convention, from which students draw inferences. In order to not duplicate previous work, our activity emphasizes using particulate and graphical representations to prompt students to develop a conceptual understanding of equilibrium as being related to the *extent* of a reaction. For the first learning cycle, we use particulate-level representations to guide students to recognize that reactions can be reversible. Students then use a graphical representation of kinetics data during the second learning cycle to develop a formal definition for equilibrium that incorporates rate (Figure 8).

As stated above, a key feature of this activity was to emphasize students' construction of a conceptual definition for equilibrium, which is reflected, in part, in the question provided in Figure 9. Previously in the activity, students focused on the general idea that it is possible for reactions to proceed in the reverse direction. Here, the goal was for the students to draw conclusions from a graph to recognize the role of reaction rate in equilibrium. This emphasizes the process of modeling, in which we use patterns in data to construct explanations and make claims, with the student discussion involving a reference to the dynamic nature of equilibrium that results in a steady amount of products and reactants.

Equilibrium: Kinetics Data

The concentration of Compounds A and X were monitored over time, with the resulting data provided below. Particulate-level diagrams are provided to visualize the two processes.

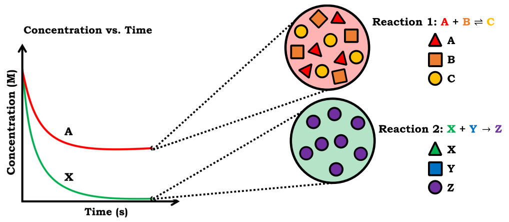

Figure 8. Example model used for the Equilibrium Activity.

Sample Questions

For Reaction 2, the reason why the rate of change of the reactants is zero is because there are no more reactants to produce product. Propose a reason for why the rate of change of the reactants is zero for Reaction 1.

Student Responses

Madison: "Because it's, since it's at equilibrium it's gonna constantly being going between the two, but it's stagnantly gonna be around the same concentration."

Figure 9. Example question from the Equilibrium Activity.

Chemical Kinetics: Constructing the Method of Initial Rates

Research into chemical kinetics has largely focused on identifying students' alternative conceptions related to the topic.[76] For example, research indicates students tend to define reaction rate as time[77,78] and inappropriately associate stoichiometric coefficients with the exponent within the rate law.[77,79−81] Relevant to the activity we developed, students' reasoning related to the method of initial rates has also been investigated, indicating students need more support in constructing and evaluating models.[72,82] Previously published POGIL activities emphasize drawing conclusions from data in kinetics tables, solving problems using the integrated rate laws, and drawing inferences regarding reaction mechanisms.[46,47] For the purposes of our activity, the aim was for students to use graphical data in the first learning cycle to construct a definition for reaction order. For the second learning cycle, we guide students in utilizing graphical data and general principles to "invent" the method of initial rates in order to construct a rate law (Figure 10). For this activity, students generate a general approach for determining the rate law from data, which can then apply to other contexts (e.g., during the application phase).

As discussed previously with the equilibrium activity, the process of modeling involves constructing explanations and models that are based on empirical observations. In the question provided below (Figure 11), students are prompted to use the data provided to develop a conceptual definition for reaction order. The group discussion in Figure 11 begins by focusing on a general trend (concentration increases, rate increases), but then they recognize other features in the graph, focusing more on relative steepness and its relationship to reaction rate. This reflects a sophisticated conceptualization of reaction order, with the group discussing how the extent in which reaction order scales rate depends on the magnitude of the concentration value, reflected in Patrick's statement, "Yeah, but the way the concentration changing slows down as the concentration gets lower." After developing a conceptual definition of reaction order, the students then use this

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Chemical Kinetics:
Kinetics Data and Rate Laws

The concentration of Compounds X and Y were monitored over time, with the resulting data provided below. Compound X is a reactant for one reaction and Compound Y is a reactant for a different reaction. Both reactions reach completion at about 90 seconds.

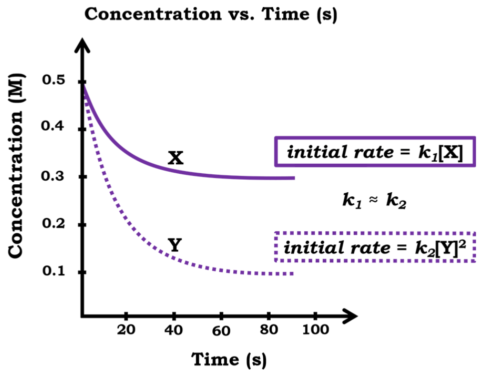

Figure 10. Example model used for the Chemical Kinetics Activity.

Sample Questions

How is rate affected by changing the concentration? How does this relate to reaction order?

Student Responses

Patrick:	"The rate would increase, wouldn't it?"
Martha:	"Well, it depends like how if you move it up or down. … The rate is obviously affected, so if you move it. Let's say like if your concentration went lower or like you had a bigger space in between, you're—"
Patrick:	"'Cause if you just look at the equation, I mean, if you multiply by a smaller number, it's going to be a smaller number, for the rate."
Cameron:	"So, as the concentration increases, the rate increases?"
Patrick	"Yeah."
Martha:	"Or isn't it, concentration decreases? 'Cause, okay, so look at Y on the graph and then look at X on the graph. So, the X has higher concentrations, but Y has a wider range of the concentrations and you can tell like it goes steeper."
Patrick:	"Yeah, but the way the concentration changing slows down as the concentration gets lower."
Cameron:	"… k_2, Y_2, Y is the concentration, so say you put like 5, then it's 25 and the rate increases, say you put 10, it's 100, 0.5 would be what, .25. Okay, so—"
Patrick:	"Yeah, it's an exponential function."

Figure 11. Example question from the Chemical Kinetics Activity.

understanding to determine the rate law using the method of initial rates.

■ LIMITATIONS

These activities have not been approved and endorsed as official POGIL activities; however, the POGIL Project has a process, the POGIL Activity Clearinghouse (PAC), through which materials can be evaluated for possible endorsement.[5] In terms of next steps, we plan on taking advantage of this process and submitting our activities to get them formally approved by the POGIL Project. In addition, with respect to fidelity of implementation, when we implemented the activities in the group discussion sections, the facilitators were graduate teaching assistants that did not have formal training at POGIL workshops. Nevertheless, during the weekly staff meeting the teaching assistants worked through the activities in groups with an instructor facilitating the process, modeling the process students would go through during discussion sections. This implementation illustrates the broad utility of the activities, since universities typically rely on graduate teaching assistants to facilitate group work, particularly for large-enrollment introductory courses.

Given that the activities are intended to be an initial introduction to the topics discussed above, we suggest instructors use the activities before formal instruction on the topic. Something we noticed when reviewing the classroom observation data was that students often looked up the answer to a question online, particularly for the *concept invention* phase of the activity. Of course, this defeats the whole purpose of scaffolding students to construct their own definition. The facilitator should emphasize that everything the students need to answer the questions is in the activity and it is more important that students work together and develop their own definition, even if they think their answer might be wrong.

Focusing on specific activities, as stated above, the orbitals activity was not implemented in a classroom discussion section, which was the due to the transition to online instruction resulting from the COVID-19 pandemic. Therefore, we opted to make use of clinical group interviews instead. In addition, there were some concerns regarding the gas law activity because students have to download the computer simulation in order to do the activity, but as long as one student in each group downloads the activity it will function as expected (we have also provided some guidance for downloading in the gas law activity instructor guide in the Supporting Information). As a potential alternative, the instructor could display the simulation on the projector for the whole class and work through the activity together with the students. In addition, there are other simulations related to real and ideal gas behavior that instructors may find useful to supplement or replace the simulation discussed in the activity.[83−85]

■ CONCLUSION

Since models are ubiquitous in chemistry and science more broadly, helping students to develop sophisticated ideas *about* models is critical for success in chemistry coursework as well as a critical component of scientific literacy.[86−88] While students in traditional general chemistry courses commonly engage in thinking *with* models, the activities we present are intended to engage students in thinking *about* models as well.[88] To promote this kind of thinking, we have embedded learning objectives related to dimensions of metamodeling knowledge in the activities, which also focus on chemistry content. This design was intentional, as evidence suggests that the development of metamodeling knowledge is complex and context sensitive.[14,89,90] Evidence has shown that students' ideas about different dimensions of metamodeling knowledge develop independently[90] and that students' metamodeling ideas may be discipline- or domain-sensitive.[14,89] In our previous work, we described qualitative differences in the characteristics of models that students discuss with regard to specific models from their chemistry course compared to scientific models in general. In Lazenby et al.,[91] we discussed our observation that

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students exhibit productive ideas about model characteristics when discussing models in general but are less likely to discuss high-level model criteria when prompted about specific chemical models. Further, students often do not even consider the representations from their chemistry courses to be scientific models at all, particularly those which are mathematical or graphical in nature.[4]

Therefore, we have designed the activities presented here in order to promote the development of students' metamodeling knowledge in chemical contexts. Further, because students do not necessarily engage in thinking *about* models without specific prompting even in rich modeling contexts,[92] we have designed the activities to explicitly promote thinking *about* the metamodeling dimensions of model changeability, model multiplicity, evaluation of models, and the process of modeling. The activities are intended to build upon students' already-existing knowledge of and about models by offering students the opportunity to create, evaluate, and revise models. We encourage instructors to utilize the resources provided and contact the authors if they have any questions.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.0c00321.

Chemical kinetics instructor guide, including an answer key with facilitation suggestions (PDF, DOCX)
Colligative properties instructor guide, including an answer key with facilitation suggestions (PDF, DOCX)
Equilibrium instructor guide; editable, answer key with facilitation suggestions (PDF, DOCX)
Gas law instructor guide, including an answer key with facilitation suggestions (PDF, DOCX)
Nuclear chemistry instructor guide, including an answer key with facilitation suggestions (PDF, DOCX)
Orbitals instructor guide, including an answer key with facilitation suggestions (PDF, DOCX)
Chemical kinetics activity, student version (PDF, DOCX)
Colligative properties activity, student version (PDF, DOCX)
Equilibrium activity; student version (PDF, DOCX)
Gas law activity, student version (PDF, DOCX)
Nuclear chemistry activity, student version (PDF, DOCX)
Orbitals activity, student version (PDF, DOCX)

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Notes

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