JOURNAL OF CHEMICAL EDUCATION
Article
Cite This: J. Chem. Educ. 2020, 97, 16−26
pubs.acs.org/jchemeduc

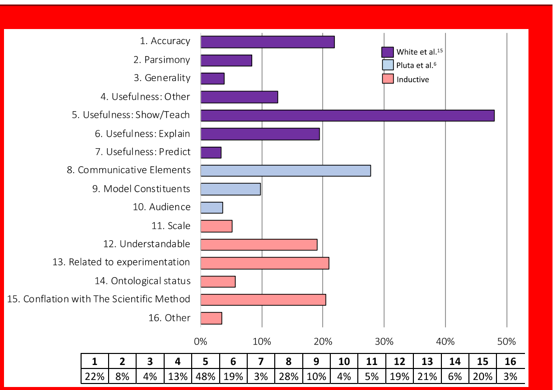
Undergraduate Chemistry Students' Epistemic Criteria for Scientific Models

Katherine Lazenby,[†] Avery Stricker,[†] Alexandra Brandriet,[‡] Charlie A. Rupp,[†] and Nicole M. Becker[*,†]

[†]Department of Chemistry, University of Iowa, 305 Chemistry Building, Iowa City, Iowa 52242, United States
[‡]Department of Chemistry and Biochemistry, Auburn University, 179 Chemistry Building, Auburn, Alabama 36849, United States

Supporting Information

To engage meaningfully with scientific models, undergraduate students must come to understand what counts as a scientific model and why. To gain a sense of the characteristics that undergraduate chemistry students ascribe to scientific models, we analyzed survey data that address students' ideas about both model criteria in general and criteria related to specific models of chemical phenomena. The findings suggest that undergraduate general chemistry students possess some productive and some intuitive ideas about the characteristics of scientific models but may not have systematic or coherent conceptions about models across contexts.



First-Year Undergraduate/General, Chemical Education Research
Chemical Education Research

INTRODUCTION

In chemistry, a discipline centered on explaining and predicting observable phenomena in terms of the processes and interactions of submicroscopic particles, models serve as critical tools for bridging the macroscopic (observable) and the submicroscopic (particulate) scales.[1] Models are tools that are useful for explaining or predicting natural phenomena; they take many forms, including but not limited to equations, graphs, diagrams, pictures, and physical objects.[2,3] Knowledge related to the nature of scientific models and the practice of modeling, including knowledge of epistemic criteria (the standards by which scientists evaluate knowledge products) for models, has been referred to as metamodeling knowledge.[2,4]

In traditional undergraduate-level chemistry courses, established models of chemical phenomena often serve as the basis for much of the course content. Students encounter a range of model types (e.g., historical models of the atom, the ideal gas law equation, and VSEPR theory), which vary in representational form, throughout a general chemistry course or sequence of courses.[5,6] Although undergraduate students are expected to be familiar with the principles embedded in established models of chemical phenomena, traditional general chemistry courses often do not explicitly address how the models came to be (nature of the models), their purpose (explaining and predicting), or how the models have been evaluated and refined over time. Our previous research suggests that even those students who can correctly use and manipulate models of chemical phenomena to solve problems may not have an understanding of how the models came to be or their intended purposes.[7−10]

To address the apparent disconnect between students' ability to solve science problems and students' understanding of the nature of science, science education reform has focused on shifting *science learning* to more closely resemble *science practice*. The National Research Council's Framework for K-12 Science Education (The Framework) highlights constructing and using models as one of eight scientific practices that are essential components of science curricula, arguing that students who engage in these practices will develop both a deeper conceptual understanding of science content and a comprehensive understanding of the nature of scientific inquiry. The Framework states that "engagement in modeling... invites and encourages students to reflect on the status of their own knowledge and their understanding of how science works,"[11] highlighting the importance of engaging students in doing science—constructing and reasoning with and about scientific models[12−14]—rather than simply learning about established scientific models.[11,15−17]

As part of this "practice turn,"[18] scholars of science education have developed several models- and modeling-focused curricula, including the Model−Observe−Reflect−Explain (MORE) thinking frame,[12] Modeling Instruction

Received: May 29, 2019
Revised: October 21, 2019
Published: November 15, 2019

DOI: 10.1021/acs.jchemed.9b00505
J. Chem. Educ. 2020, 97, 16−26

(MI),[13] and Model-Based Inquiry (MBI).[14] Evaluations of these approaches have shown that they positively affect students' content learning,[19,20] attitudes about science learning,[21,22] metacognitive skills,[23] and ability to use multiple representations for problem solving.[24] In addition, these curricula narrow performance gaps for historically underrepresented groups in STEM.[19] In the field of chemistry, research has shown that the MORE thinking frame effectively supports students in revising their ideas about unobservable phenomena based on empirical evidence.[25]

A core aspect of meaningful engagement in science practice is knowledge of the "hows and whys" of practices such as modeling: the steps to take and features to include when constructing a knowledge product such as a model, and criteria for evaluating the knowledge product. For example, Berland et al.[26] offer the following illustration:

". . .when constructing a model of how light travels, middle school students have to decide what kind of information is needed in the model. They might think about including key components (i.e., including labels and light rays), incorporating their past experiences (i.e., they may have seen light bending in water), and/or considering how the system works (i.e., the interaction between light rays and the type of material through which it is traveling). In addition, students' understanding of why they are engaging in modeling in these ways can vary."

As Berland and colleagues[26] highlight, constructing, evaluating, and using models requires students to make decisions about what to include in a model and why. Some scholars posit that these decisions are framed by students' implicit ideas about what counts as a scientific model and who might use scientific models.[7,27,28]

Scholars have argued that learning about epistemic criteria, or the standards by which scientists evaluate knowledge products, is an important component of engaging in scientific practices such as modeling.[26,27] Epistemic criteria become important, for instance, in assessing the quality of models and selecting between multiple models for a given phenomenon. The criteria may include characteristics such as a model's ability to accurately reflect the structure or behavior of a system or process while accounting for as wide a variety of phenomena as possible. Additionally, researchers strive to develop models that are parsimonious, that generate important applications for users, and that are coherent with what is already known in a field of study.[29]

Because scientific models are the primary shareable products of scientific inquiry,[26,27] it has been suggested that supporting development of metamodeling knowledge will allow them to engage more meaningfully with socially and globally relevant models.[2,26,30] Given the importance of epistemic criteria to the development and evaluation of knowledge products,[26] it is critical for formal science training to explicitly focus on developing scientific epistemic knowledge and to have mechanisms for assessing changes in epistemic knowledge.[11,27,30]

One potentially fruitful approach is to provide opportunities for classroom discussion around the standards scientists use to evaluate knowledge products (epistemic criteria)[27] such as arguments,[31] models,[4,27] and explanations.[32] To facilitate the development of epistemic knowledge related to scientific models, specifically, some scholars have advocated for engaging students in the construction, use, and evaluation of models,[4,14,28,33−36] an approach we refer to as modeling-focused classroom instruction. Modeling-focused classroom instruction developed to accomplish these goals include the MORE thinking frame,[12] Modeling Instruction,[13] and Model-Based Inquiry.[14] As mentioned earlier, prior science education research has shown that modeling-focused instruction may improve both content knowledge and knowledge of the nature of scientific inquiry (i.e., epistemic knowledge).[4,33,35−37]

For modeling-focused classroom instruction to be successful, curricular designers and instructors must have a sense of the intuitive ideas students bring to undergraduate science courses.[38,39] However, while several studies have investigated K-12 students' ideas about epistemic criteria for models and modeling,[4,27,28,40] there is little extant research on these ideas among students at the university level. Further, recent research revealing the context dependency of students' epistemic ideas about models highlights the importance of understanding how university-level chemistry students think about the criteria by which models are evaluated across both domain-general and context-specific tasks.[41−43] A current challenge is that existing resources for assessing students' epistemic knowledge of models primarily address students' domain-general knowledge and do not examine context-specific knowledge or context dependence of knowledge.[44−46]

In the current study, we identify and examine themes in first-year university chemistry students' reasoning about epistemic criteria of scientific models. Further, we compare students' ideas about model characteristics in two contexts: in a domain-general context and in several contexts specific to a first-year university chemistry course.

This analysis of students' ideas in the context of a traditional, lecture-based undergraduate chemistry course may serve as a baseline reference point for curricular interventions aimed at supporting the students' development of robust and coherent knowledge about models and modeling and the role of models in scientific inquiry. In addition, the analysis can serve as the basis for the design of assessments that account for context-dependence in students' epistemic knowledge of models. The following research questions guide this study:

1. What epistemic criteria do undergraduate chemistry students consider when thinking about scientific models in general?
2. How do the epistemic criteria students identify when thinking about scientific models in general compare to the criteria they identify for chemistry-specific models?

In the following section, we review the extant literature on students' epistemic criteria for scientific models. We also outline the theoretical perspectives on learning that inform our research and discuss how these perspectives inform our analyses and interpretations of results.

■ LITERATURE REVIEW

Prior Research on Students' Epistemic Criteria Related to Models and Modeling

Most of the studies that have examined students' intuitive ideas about epistemic criteria for models have focused on K-12 contexts.[27,40] In a foundational cross-age study, Grosslight et al.[40] interviewed 7th and 11th grade students and adult experts about what they would consider key characteristics of scientific models. The students in the study had no explicit instruction on models or modeling. The authors found that few students (3% of 7th graders and 14% of 11th graders) discussed the purposes for which scientific models are constructed. A greater proportion of students discussed the relationship between the model and the target system, for instance, noting that a model should represent or "look like" the target phenomena to the extent possible (30% of 7th graders, 32% of 11th graders). In addition, the authors found that 7th graders primarily conceived of models as copies of real-world phenomena, and though some 11th graders were more able to distinguish between the model and the target, many still thought of models as needing to represent a target phenomenon as closely as possible. There was little overlap between experts' ideas and students' ideas.

In a more recent study, Pluta et al.[27] examined middle school students' ideas about the criteria they used to evaluate models and then compared students' epistemic criteria to those identified by philosophers of science in peer-reviewed literature. In addition to participating in their usual science instruction, students in this study completed a short activity in which they were presented with pairs of models of familiar phenomena (e.g., the life cycle of butterflies, food webs, the water cycle) and evaluated which of the models was "better" or if they were equally good. After completing the activity with a partner, each student individually generated a list of six characteristics of scientific models.

The authors categorized the model characteristics generated by students as either primary criteria (i.e., those the authors saw as central across science disciplines and relating to the accuracy of the model) or secondary criteria (i.e., criteria that contribute to epistemic aims of science but do not have a direct impact on the accuracy of the model). The results showed that while the writings of experts focused on primary criteria, such as the idea that models should be supported by evidence and should enable useful explanations for phenomena, students were less likely to discuss these criteria.[27] In contrast, students commented more frequently on secondary criteria, for instance, noting that models should be easy to understand for a variety of audiences and should appear detailed and well organized. Students also commonly reported that models must have specific representational forms, such as pictures, words, or diagrams, or specific components such as labels. The authors argued that students' focus on secondary criteria relating to the appearance of models rather than the explanatory and predictive purpose of models may represent an opportunity for scaffolding students' ideas toward a more sophisticated understanding of how models are developed and evaluated.

Fewer studies have focused on undergraduate students' intuitive epistemic ideas regarding scientific models and modeling.[7,8,41,45,46] In our own previous research in an undergraduate chemistry context,[7] we observed that undergraduate students in a first-year university chemistry course for STEM majors often expressed ideas about the utility of scientific models as teaching tools in conjunction with chemistry-specific models but infrequently discussed the same models as tools for explaining or predicting phenomena. Further, few students considered common mathematical and graphical models to be scientific models. Students were more likely to rely on heuristics about the representational form of models, for instance, the idea that models must be visual representations, when reasoning about whether to categorize equations and graphs as scientific models than when reasoning about other, more visual models.

Theoretical Perspectives

Our perspective on student learning is informed by the epistemological resources and framing perspective,[39,47] which was developed to describe the ways that students conceptualize the nature of physics knowledge. Within this framework, knowledge structures are conceptualized as networks of fine-grained cognitive resources that people develop based on their experiences in the world. Some of these resources are epistemic and pertain to students' ideas about the nature of knowledge and knowing. These epistemic resources may be ideas about the nature of knowledge and how an individual comes to "know" (e.g., the idea that a person can know something because someone authoritative communicated the information, versus the idea that knowledge can be generated by collecting and analyzing data). We view students' epistemic ideas about scientific models and modeling as a subset of students' epistemological resources.

Context and framing determine both whether resources (or clusters of connected resources) are activated (or not) and, if activated, whether they are productive or nonproductive according to whether they are useful in achieving the intended outcome. A student's "framing" of a given context can determine whether a resource is activated. Elby and Hammer described epistemological framing as answering the question, "What is going on here?"[47] For instance, a student is likely to activate different resources to investigate chemical phenomena if they frame the activity as "doing school" than if they frame it as "doing science."[48]

The interplay between context and activation determines whether students' ideas are productive for sense-making about the natural world.[39] For example, while trial-and-error may not be a particularly useful or efficient strategy for investigating certain chemical phenomena, it is a useful and productive strategy in other contexts, such as trying different recipe modifications when baking.

■ METHODS

In the present study, we analyze survey data from a subset of items on the Models in Chemistry Survey (MCS), an instrument that our research team developed to identify undergraduate students' ideas about epistemic criteria for scientific models and assess the extent to which students' ideas vary in domain-general and chemistry-specific contexts. The findings from other items on the survey are detailed in other manuscripts.[7,8] We include the full Models in Chemistry Survey as Supporting Information.

Participants and Setting

The study participants were undergraduate students enrolled in a first-semester introductory chemistry course for STEM majors; the course is the first in a two-semester sequence at a large research-intensive university in the Midwestern United States. In addition to attending a traditional, large lecture-style class that met 3 days per week, students participated in a once-weekly discussion section, which was facilitated by teaching assistants and focused on problem solving, as well as case study and laboratory sections which met on alternating weeks. Case studies were intended to help students prepare for the following week's laboratory and apply and recognize chemistry concepts in real-world scenarios. Brown et al.'s[49] *Chemistry: The Central Science* (12th edition) was the textbook for the course. The course did not include an explicit focus on scientific models or their characteristics. Early in the semester,

Table 1. Themes Pertaining to Students' Discussion of Model Usefulness

Code	Definition
Show/Teach	Student response explicitly mentions the potential uses of models such as showing, displaying, describing, or representing a phenomenon, teaching about a phenomenon, or making the phenomenon easy to understand
Explain	Student response refers to models as useful for explaining why or how a phenomenon occurs
Predict	Student response refers to the utility of models for predicting phenomena. This includes both responses that make a general reference to prediction and responses that explicitly refer to specific phenomena that models can be used to predict.
Other	Responses address the use of models for solving problems; alternately, students mention model usefulness without further discussion

several historic models of the atom were introduced and the evolution of accepted atomic models was discussed, but students were never prompted to explicitly consider the characteristics of well-designed models.

Development and Administration of the Models in Chemistry Survey

The pilot version of the Models in Chemistry survey contained twenty-three items, including both forced-choice and open-ended items. The items were constructed based on relevant studies of students' knowledge of models and modeling.[4,29] At the end of the survey, students were asked to provide demographic information and to indicate whether they would be interested in participating in an additional interview focused on establishing the response-process validity of the tasks.

In spring 2017, we administered the pilot MCS to students in the introductory chemistry course and selected eight of these students to participate in semistructured interviews that were used to collect data on students' response processes as they answered each item on the MCS. Interviewees were selected based on a maximum variation sampling approach; specifically, we identified students whose survey responses represented the observed range of responses. In the interviews, participants were asked to interpret the meaning of each prompt and describe their reasoning for their answers as they worked aloud through each MCS item. We recorded the interviews with a video camera and a Livescribe[50] pen. We compensated each participant for their time with a $10 gift card.

On the basis of an analysis of data from the interviews and the responses to the pilot survey, we modified several MCS items. Modifications were based on the identification of instances of either construct underrepresentation (i.e., failure to measure the full range of the target construct) or construct-irrelevance (i.e., measurement of constructs other than the target construct).[51] After modification, the MCS contained 23 forced-choice and open-ended items followed by several items about the participant's demographic characteristics.

In fall 2017, we administered the modified version of the MCS via Qualtrics[52] to undergraduate introductory chemistry students. The survey opened during the week before final exams; thus, the findings we report here represent the epistemic criteria that students assigned to scientific models after completing a full semester of undergraduate chemistry. All survey respondents were given the option to consent or decline to participate in the study and were awarded three extra credit points, regardless of their participation in the research study. From the 1,017 students enrolled in the course, we collected 864 response sets. Twenty students submitted multiple response sets, and in these cases, we excluded the second response sets from the data. We identified 16 response sets that provided only very incomplete or off-construct responses to all items and excluded these from the data set. We also excluded the response sets of 12 underage students (<18 years of age) and seventy-nine students who declined to participate in the research study. The final data set includes the response sets of 757 students (74% of all students enrolled in the course). Most participants were in their first semester of college (80%) and 18−21 years old (94%). Among the participants, 46% identified as male, 53% as female, and <1% as nonbinary. An additional 1% of students did not respond to the gender identification prompt. All data were collected with Institutional Review Board approval.

Data Analysis

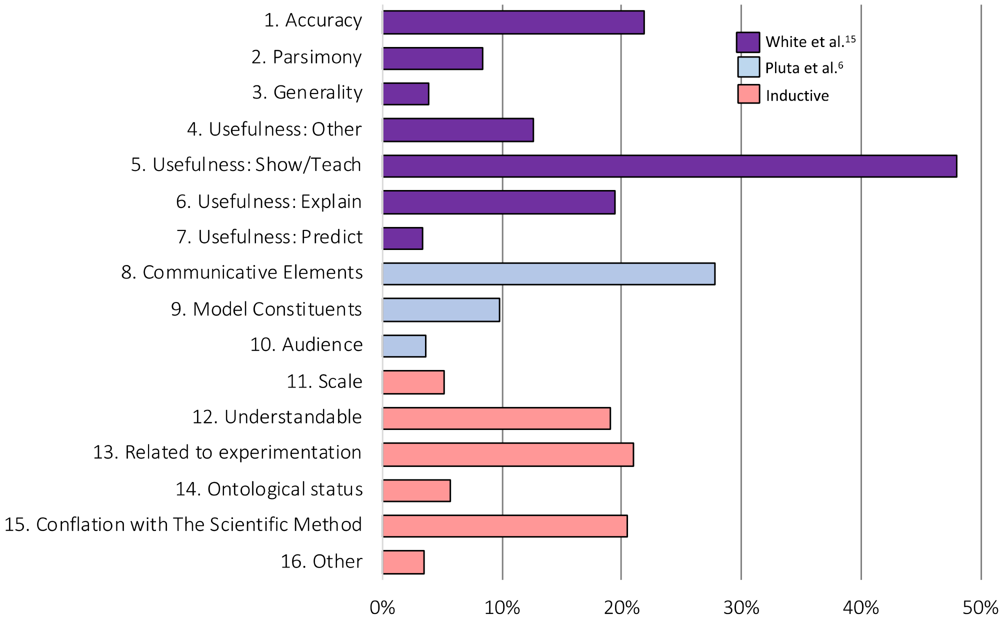
We used both deductive codes derived from the research literature and inductive codes based on a review of the data to analyze students' responses to the two question prompts: "What do you think a scientific model is?" and "What are some characteristics of a good scientific model?" We applied as many codes as necessary to fully represent students' ideas (a one-to-many coding structure).

Development of Deductive Codes from Extant Literature. We adapted White et al.'s[29] and Pluta et al.'s[27] descriptions of the epistemic criteria that define scientific models. Because students' responses to these two tasks were similar and informed by one another, we combined the responses to the two prompts for the focal analysis. Refer to the Supporting Information for code definitions and examples.

White et al.[29] discussed five key characteristics of scientific models: accuracy, coherence, generality, parsimony, and usefulness. Accuracy relates to how closely or correctly a model represents a certain aspect of the target phenomena. Generality addresses the model's ability to explain or predict a range of related phenomena. Parsimony reflects the idea that models simplify some elements of the target phenomena in order to highlight others. Usefulness refers to the ways in which a model can be used to explain or predict real-world phenomena. A review of the data showed that students did not discuss the idea of coherence to an appreciable extent and therefore we do not discuss this theme in the findings.

The criteria described by Pluta et al.[27] and adapted for our coding scheme included communicative elements of models, model constituents, and the intended audience of models. The first criterion, Communicative Elements, refers to the idea that models must clearly and concisely convey the intended information about a target phenomenon. The second criterion, Model Constituents, reflects the idea that models should use images or labels to support their communicative ability. The third criterion, Audience, refers to the intended users of scientific models. The Supporting Information contains full definitions and examples of these deductive codes.

In our prior analysis of students' ideas about chemistry-specific models,[7] we observed that students discussed model usefulness far more frequently than any other characteristic, and that there was significant variation in the ways that students discussed this topic. Therefore, in Lazenby et. al[7] we



1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
22%	8%	4%	13%	48%	19%	3%	28%	10%	4%	5%	19%	21%	6%	20%	3%

Figure 1. Code frequency (percentages) for students' identified characteristics of scientific models, $N = 757$.

used an inductive constant comparative approach to characterize the diverse ways in which students discussed model utility. Noticing a similar range of ideas in students' discussion of domain-general models in the present analysis, we used the same codes to capture students' ideas. Table 1 describes codes related to model usefulness developed in Lazenby et al.[7]

Development of Inductive Codes Pertaining to Students' Ideas about Model Usefulness. In addition to using deductive codes based on the extant literature, we also used an inductive approach to capture additional themes that did not align with any of the deductive codes.[53]

Reliability. The first author coded the entire data set and the second author independently coded approximately 20% of the data set (150 randomly selected responses). Because we applied as many codes as necessary to capture all themes in each response (a one-to-many coding structure), we calculated the Fuzzy kappa statistic as the index of inter-rater reliability.[54] Fuzzy kappa is based on Cohen's kappa[55] and modified for use with one-to-many coding structures. The calculated Fuzzy kappa value of 0.82 and inter-rater agreement value of 85.4% suggest "near-perfect" reliability.[56]

■ FINDINGS AND DISCUSSION

In the following sections, we discuss the key themes pertaining to the two research questions.

RQ1. What Epistemic Criteria Do Undergraduate Chemistry Students Consider When Thinking about Scientific Models in Domain-General Tasks?

Figure 1 summarizes the frequency of the deductive and inductive codes used in the analysis of student responses to the questions "What do you think a scientific model is?" and "What are some characteristics of a good scientific model?" Of the four deductive themes adapted from the work of White et al.,[29] themes of model usefulness and accuracy were the most commonly discussed by participants as key criteria by which models can be evaluated. The constructs of parsimony and generality were discussed less frequently, and, as noted in the Methods section, model coherence was not discussed to an appreciable extent.

Model Usefulness. Most students mentioned model utility in some capacity (70%; $n = 532$). Most commonly, students discussed models as useful for showing or describing phenomena or as useful for teaching (Usefulness—Show/Teach, 48%; $n = 363$). Responses in this category often described models as visual or physical representations that make phenomena easier to understand. For example, one student responded, "A scientific model is a representation of an idea or concept. It helps show a phenomenon that may be not easy to understand without a model."

Many participants discussed models as useful for explaining phenomena (Usefulness—Explain, 19%; $n = 147$). Some responses in this category seemed to discuss what have been referred to as disciplinary explanations,[57] or explanations that are theory- and evidence-driven accounts of how and why phenomena occur. One student stated, for example, "A good scientific model would be one that can explain why or how something happens the way that it does." Other students seemed to discuss instructional explanations,[57] which are intended to help students understand concepts and ideas, for example, "[A good scientific model is] something that explains a scientific phenomenon that is difficult for us to perceive… They connect stuff we already know to what we are trying to learn." Often, when students used the word "explain," it was not clear whether they were referencing disciplinary explanations or instructional explanations, for example, "A scientific model is used to describe and explain a phenomenon." Therefore, we did not incorporate the disciplinary/instructional distinction into the coding structure. Importantly, however, there was variation in students' discussions of the explanatory power of scientific models, which may represent differences in the ways students frame the use of models as explanatory tools.[47]

Few students discussed models as useful as predictive tools (Usefulness—Predict, 3%; $n = 25$). The following explanation is typical of responses in this category, "It allows scientists to make accurate predictions about what will happen." Although first-year university chemistry students regularly use models to make predictions in their coursework, the responses indicate that the predictive power of these scientific models is not particularly salient for students.

Some students discussed additional ways that models are useful, such as for answering questions, solving problems, or "proving" things. While these responses are perhaps inconsistent with the ways that scientists use models, we interpret them as representing students' intuitive conceptions about the nature of scientific inquiry and reflective of their curricular experiences. We understand these types of responses as reflective of the ways that students frame school science as "doing school" as opposed to "doing science"[47,48] We categorized these responses as Usefulness—Other (13%; $n = 95$).

In sum, we identified three main uses of models in students' responses about model utility: to show or teach, to explain, and to predict scientific events. A similar variation in students' ideas about model utility has been discussed in the literature; for example, Upmeier zu Belzen and colleagues[58] described a three-level hierarchical progression of biology students' understanding of the purpose of scientific models. The authors found that lower-level ideas expressed by students focused on models being useful for describing the target phenomenon (showing), while midlevel and high-level ideas focused on models' utility for explaining and predicting phenomena, respectively.

While we agree that recognizing the significance of generative activities (e.g., constructing explanations for and predictions of natural events) reflects a more sophisticated perception of the epistemic nature of science than understanding science as simply representing, showing, or replicating observed phenomena, in our analysis of the focal data, we do not interpret the identification of predictive utility as necessarily constituting a more advanced understanding of the purpose of models. In part, this is because some chemistry models are more suited to explaining (e.g., kinetic molecular theory) while others are more obviously suited to making predictions (e.g., the Ideal Gas Law).[3] Further, we interpret both ideas about explaining and ideas about predicting as indicative of students framing science as a generative activity, and based on the written responses of students to our domain-general tasks, we do not believe that fine-grained differentiation is warranted.

Other Model Criteria from White et al.[29] Students who addressed model accuracy (22%; $n = 166$) most often referred to the similarity between a visual or physical representation and the target phenomena, for example, "A scientific model is a physical depiction of a scientific idea... A good scientific model would include materials that accurately represent the structure being modeled." However, a few students noted that a model should make accurate predictions or accurately explain a phenomenon, for instance, one student explained, "A scientific model predicts what would most likely occur in the natural world... It accurately predicts outcomes."

Responses that addressed parsimony (8%; $n = 63$) commonly referred to models' ability to simplify phenomena for learning purposes, for example, "A scientific model is something used in science to represent a set of information in a different or more simple way that makes it easier to understand," or "A good scientific model explains the theory in a simpler way." Some students addressed the idea that modelers sometimes make assumptions in order to highlight certain elements of the target phenomenon. One student stated, "[A scientific model] must be simple and show the most important parts of [the] theory/idea." We interpret this response as recognizing that simplification of some aspects is necessary to highlight other aspects of the target phenomenon.

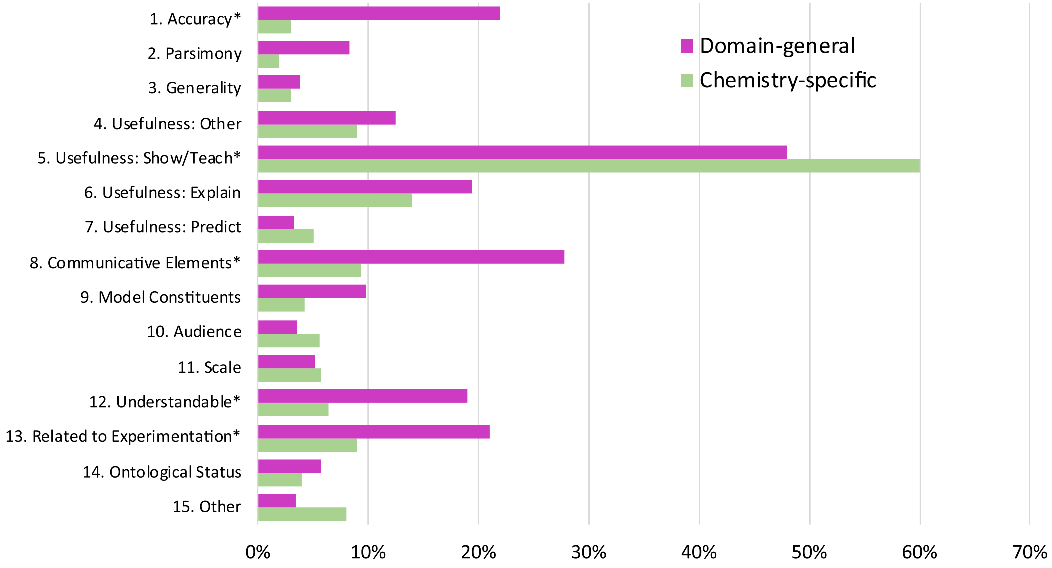
Students who addressed generality (4%; $n = 29$) commonly referred to the models' ability to represent or explain related phenomena with only a few exceptions. One student in this category claimed, "A good scientific model should correctly predict what will happen in most or all instances."

As we have noted, the students in our sample did not discuss model coherence, which White et al. described as the model fitting "with everything that is known about the domain" and "coher[ing] with other models to form an integrated theory of the domain."[29] We believe that the structure of curricula may contribute to the fact that we did not observe students speaking to this idea. In traditional chemistry courses such as that sampled in this study, models such as diagrams and equations are commonly used in isolation,[59] despite the fact that such models are often intended to bridge the macroscopic (observable) and the submicroscopic (particulate) scales. Further, the fact that we did not see students discussing the coherence of models with theories and facts within a domain may reflect fragmentation of the students' own knowledge structures. Indeed, it is well-established that the students' developing science knowledge is often not well organized or coherent.[1,60,61]

Deductive Codes Adapted from Pluta et al.[27] We adapted three themes from the findings of Pluta et al. from a study of middle school students' epistemic criteria for modeling, all of which were considered by the authors to be "secondary criteria," that is, criteria that relate to the representational quality of the model rather than content accuracy. Communicative elements of scientific models (such as which details are included and the clarity and organization of the model) were most commonly mentioned by the participants. Responses that mentioned communicative elements of scientific models often referred to the idea that a model should communicate the intended information clearly. For example, one student stated they believed "a good scientific model must be clear, and you must be able to fully understand the topic or idea it is trying to convey." We observed that the code for Communicative Elements (28%; $n = 210$) commonly co-occurred with the code for Usefulness—Show/Teach ($n = 135$), suggesting that students who focus on these elements may frame models as tools primarily used in teaching and learning settings.

The second theme we adapted from Pluta et al.[27] Model Constituents (10%; $n = 74$) centers on features that improve the interpretability of the model, such as arrows and labels. For instance, one student stated that a scientific model should have "graphs, charts, pictures, etc. rather than words, labels, data, colors."

Students who discussed the idea that models are designed for an intended audience (Audience, 4%; $n = 27$) commonly identified students or the general population (rather than scientists) as the target audience of scientific models. One student explained, "It should be clear, labeled, and able to be understood by those not necessarily experts in the subject."



	1*	2	3	4	5*	6	7	8*	9	10	11	12*	13*	14	15
Domain-general	22%	8%	4%	13%	48%	19%	3%	28%	10%	4%	5%	19%	21%	6%	3%
Chemistry-specific	3%	2%	3%	9%	60%	14%	5%	9%	4%	6%	6%	6%	9%	4%	8%

Figure 2. Code frequency (percentages) for students' identified characteristics of scientific models in domain-general and chemistry-specific contexts. The asterisk (∗) indicates a difference of >10% between task types, *N* = 757.

Emergent Themes. In addition to adapting the model characteristics described by White et al.[29] and Pluta et al.,[27] we identified four additional characteristics that students ascribed to scientific models. Participants expressed that a model should be (1) easy to understand, (2) proportional or "to scale" compared to the target phenomenon, (3) informed by experimental results, and (4) proven or accepted as truth by the scientific community. A fifth emergent theme was based on a subset of responses that seemed to focus on the scientific method rather than scientific models, suggesting that perhaps these students conflated the two concepts.

Many students noted that models should be understandable (19%; *n* = 144), a theme that may be related to students framing scientific models as teaching tools. We argue that the characteristic of Understandable is distinct from Usefulness—Show/Teach because the responses in this emergent category stated that scientific models themselves should be easy to understand and user-friendly. For example, one student commented that "good scientific models are easy to understand, and students can relate them to real life applications." The idea that models should be understandable often coincided with Usefulness—Show/Teach (*n* = 98) and/or Communicative Elements (*n* = 73).

A second emergent theme is that models should be proportional to or scale relative to the target phenomenon (Scale, 5%; *n* = 39); this theme is related to the idea that models are visual or physical representations. Students in this category explained that models may scale the target phenomenon up or down for greater conceptual accessibility. For example, one student wrote, "A scientific model is something that mimics a real thing but is done to scale so that it can be studied." This theme also frequently coincided with the idea that models are useful for teaching (Usefulness—Show/Teach, *n* = 35).

The third emergent theme was that models should be related to experimentation or empirical evidence. Responses in this category indicated that models should be built upon or supported with evidence (Related to Experimentation, 21%, *n* = 159). One student stated, "I think that a scientific model is a chart, graph, physical design model, or anything related to those that is created based off of observations and collected data." Other students commented that models may be empirically tested, for example, "A scientific model is an explanation of something that occurs with material related to the natural, that can be tested and falsified." Student recognition of the empirical nature or basis of models and modeling has been reported in prior research.[27,40,41,43,62]

The final emergent theme centers on the acceptance of models as truth and/or fact by the scientific community (Ontological Status, 6%; *n* = 43). We interpret students' focus on such acceptance as a reference to the ontological status of scientific models, that is, the nature of models as entities in knowledge construction. These responses typically discussed the idea that scientific models should be "proven," "theory," "law," or "fact." We argue that these responses likely reflect confusion between scientific models and theories, laws, and facts, and thus highlight an important challenge in science education, that of helping students to distinguish between constructs such as models, theories, and laws as part of target epistemic knowledge.[11]

Lastly, a subset of students responded to the tasks as if we had asked them about the scientific method rather than scientific models (Conflation with the Scientific Method, 20%; *n* = 155). Responses in this category often listed the steps an individual might take to design an experiment. For example, one student explained, "I think that the scientific model is the process of solving a problem using an experimental method. A good scientific model typically has a hypothesis, multiple trials, reproducible procedure and results, and a coherent conclusion." Some students explicitly noted that the question was not about the scientific method but stated that scientific models and the scientific method were essentially the same thing, as in the following response: “A scientific model is like the scientific method, which is the process of scientific thinking with proposing a hypothesis and collecting data, etc.” We believe these responses may reflect conflation between scientific theories and the scientific method, and in some cases a belief that the two are the same. An additional 3% (n = 26) of responses were either off-construct or were too vague to assign to any category; we coded these responses as Other.

RQ2. How Do the Epistemic Criteria Students Identified in Domain-General Tasks Compare to the Criteria Identified for Specific Chemical Models?

In an earlier manuscript,[7] we reported the epistemic criteria that students identified for six chemistry-specific models introduced in their undergraduate introductory chemistry course. Students categorized six representations as a model (or not): a Lewis structure, a representation of the motion and spacing of gas particles, a physical model of a molecule, an energy level diagram, the Ideal Gas Law equation, and an equilibrium constant expression. In our prior study, we compared the frequencies of codes assigned to student explanations of why they would consider each to be a model. Notably, we observed significant differences in the proportions of students who considered visual models as models compared to graphical and mathematical models,[7] suggesting context-dependency of students’ ideas about models.

In this section, we report on the comparison of students’ reasoning about the domain-general tasks reported here to the chemistry-specific models reported in Lazenby et al.,[7] using the same coding structure reported in our previous work. This analysis is motivated by an interest in the extent to which the ideas of epistemic students are influenced by domain-specific context.

Figure 2 shows a comparison of the proportions of students who discussed each model criterion in the domain-general and model-specific tasks. Conflation with the Scientific Method was not observed in response to chemistry-specific tasks and is thus omitted. For the chemistry-specific tasks, we report only responses in which students indicated that they considered the representation to show a scientific model (e.g., Lewis structure, Ideal Gas Law). We discuss the proportion of student classification of these six different chemical models in greater detail in Lazenby et al.[7] Notably, a significantly higher proportion of students classified models that were representations of molecular structure (physical model of molecule, Lewis structure, and representation of motion and spacing of gas particles) as scientific models compared to mathematical and graphical models (energy diagram, the Ideal Gas Law equation, and an equilibrium constant expression), and thus findings shown here may be skewed toward students’ ideas about these model types specifically.

Comparison of Responses to Domain-General and Chemistry-Specific Tasks. In the domain-general task (“What do you think a scientific model is?” and “What are some characteristics of a good scientific model?”), we assigned an average of 2.4 codes per response. In comparison, for the chemistry-specific tasks (“Why would you consider a ______ to be (not) a scientific model?”), we applied an average of 2.1 codes per response.

Responses to the domain-general task were more likely (differences greater than 10%) than responses to the chemistry-specific tasks to discuss four characteristics: Accuracy, Communicative Elements, Understandable, and Related to Research or Experimentation. While these differences may be partially due to two external factors—wording of prompts and students discussing more criteria in domain-general tasks—some of the differences are especially large, indicating that students might think about model criteria differently in these two contexts.

In the domain-general tasks, 22% of students discussed Accuracy; these students typically mentioned that models should accurately or correctly represent the target phenomenon. In comparison, only 3% of students discussed this idea when asked about models from their chemistry class (chemistry-specific tasks). In the chemistry-specific tasks, we observed frequent co-occurrence of Accuracy with codes such as Ontological Status and Related to Research and Experimentation (that is, the idea that already established models are “proven” or based on the work of scientists), and thus students may have considered chemistry-specific models to be implicitly accurate.

Similarly, we observed differences in the proportions of responses which were coded using Communicative Elements, Understandable, and Related to Research or Experimentation in domain-general compared to chemistry-specific tasks (differences of 18%, 13%, and 12%, respectively). In domain-general tasks, students frequently stated that models should be clear and organized (Communicative Elements); easy to understand or interpret (Understandable); and testable, repeatable, or based on empirical data (Related to Research or Experimentation). Students may have been more likely to discuss communicative elements and understandability in the domain-general task because, as Pluta and colleagues note, these can be considered secondary characteristics, rather than determining features of what makes a representation a model (or not).

We also observed a relatively large difference (12%) in the proportion of students who discussed Usefulness—Show/Teach in domain-general tasks (48%) compared to chemistry-specific tasks (60%). Usefulness—Show/Teach was the only characteristic that students discussed more frequently in chemistry-specific tasks than domain-general tasks. Only a small percentage of students discussed the predictive utility of models (Usefulness—Predict) in the domain-general (3%) and chemistry-specific tasks (5%), suggesting that undergraduate chemistry students do not necessarily frame the use of models as related to predicting phenomena. A larger proportion of students discussed the explanatory usefulness of models in the domain-general tasks (19%) than in the chemistry-specific tasks (14%), suggesting that some students recognize that scientific models may be useful for explaining but may not frame the models used in their chemistry course as potential explanatory tools.

■ LIMITATIONS

One potential limitation of the study is our assumption that students’ written survey responses fully reflect their epistemic ideas about the characteristics of scientific models. Indeed, students might possess additional ideas about model criteria that were not elicited by the survey prompts. However, the themes identified in our analysis of students’ written responses generally mirror those observed in the think-aloud interviews. One exception to the general parallelism observed across survey and interview data is that none of the students who participated in interviews conflated scientific models and the

DOI: 10.1021/acs.jchemed.9b00505
J. Chem. Educ. 2020, 97, 16−26

scientific method. We acknowledge that the survey prompt may have been unclear and caused some students to be confused about the difference between scientific models and the scientific method.

A second potential limitation is that the item stems for the domain-general and chemistry-specific items were not completely parallel. Effects of differences in item stems are well documented.[63−65] However, students did not discuss any model characteristics for domain-general items that they did not discuss for chemistry-specific items, and vice versa—the only differences were the frequencies with which students referred to these model characteristics. Further, in the interviews, there were no differences in students' response processes in answering the domain-general items and the chemistry-specific items.

■ SUMMARY AND CONCLUSIONS

Here, we presented a qualitative analysis of the characteristics that first-year university chemistry students assign to scientific models in domain-general and chemistry-specific contexts. Of the five defining epistemic characteristics of models described by White et al.,[29] students most often discussed the idea that models should be useful. They discussed accuracy less frequently and mentioned ideas of model generality and parsimony infrequently. No students discussed model coherence. Students also acknowledged model characteristics related to models' communicative ability, which were previously described as "secondary criteria" for models in a study of middle school students conducted by Pluta et al.[27] We identified several emergent themes in students' responses, including model understandability, experimental basis, and ontological status, as well as the idea that models are "to scale" representations of phenomena. The proportions of students who discussed specific model characteristics varied across item types (domain-general vs chemistry-specific). We argue that this pattern suggests that some students have productive ideas about ideal model characteristics, but do not recognize these characteristics in the models introduced in their chemistry course.

■ IMPLICATIONS FOR INSTRUCTION AND RESEARCH

When interpreted through the lens of the Epistemological Resources and Framing perspective,[39] the results presented here suggest that students likely have quite a few productive resources related to epistemic criteria for scientific models. For example, the sample students overwhelmingly recognized that models should be useful for doing *something*. These findings suggest that helping students frame model utility as generative (i.e., using models as explanatory and predictive tools) rather than pedagogical[3] (i.e., using models for learning what is already known) may help students develop more science-like ideas about domain-specific model criteria, while building on existing resources.

Our analysis indicates that although students' conceptual resources are potentially productive, they are highly sensitive to context, as evidenced by the variation in themes across domain-general and chemistry-specific tasks. For example, while many students discussed the empirical basis of models in domain-general tasks, few mentioned this idea in relation to specific chemical models.

While some students seemed to possess and use productive and coherent epistemological resources related to models across both contexts (domain general and chemistry-specific), others seem to possess some potentially productive resources but need scaffolding to activate them in chemistry-specific contexts.

Thus, instructors should identify strategies to help students negotiate the meaning of scientific models in new contexts and to extend the span of conceptual resources to new types of models.[66,67] This type of guidance could involve helping students frame their use of models as "doing science", that is, predicting and explaining phenomena, as opposed to "doing school", that is, merely answering problem sets.[39] Modeling-focused curricular resources that engage students in modeling practice, such as the Model−Observe−Reflect−Explain (MORE) thinking frame,[12] which engages students in constructing initial models, gathering evidence, and refining and explaining their models, has demonstrated potential to help students to recognize that models should be supported by evidence and to revise their models accordingly.[25]

The focal sample of students (undergraduate chemistry students, most of whom are STEM majors) expressed many of the same ideas about model characteristics as the middle school students at similar proportions when asked what defines a scientific model.[27] For instance, both groups discussed communicative elements, understandability, which are indeed features of models, but are not defining characteristics as are criteria such as accuracy or coherence with known theories and facts. To us, this may suggest that epistemic knowledge does not develop without explicit instruction.

Therefore, we urge both researchers and practitioners to consider instructional approaches that will support the development of more sophisticated ideas regarding the evaluation of scientific models.[38] One approach practitioners should consider is facilitating classroom discussion around the evaluation of scientific models and the relevant epistemic criteria for evaluation. This type of intentional conversation may be particularly valuable if designed to build upon the productive resources that students already possess.[38,39,47] Prior research has shown that instructional approaches that engage students in coconstructing and critiquing knowledge products (e.g., explanations,[32] arguments[31]) provoke students to consider the epistemic criteria by which scientists evaluate knowledge.[26]

Another important implication for researchers and practitioners interested in the assessment of students' ideas about model characteristics is that domain-general assessments might invoke ideas that are not representative of students' ideas about specific disciplinary models.[44−46] Data from such assessments should be interpreted cautiously, with the acknowledgment that students' ideas about scientific models and modeling are sensitive to context.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications Web site at DOI: 10.1021/acs.jchemed.XXXXXXX. Survey instrument (MCS) (Models_in_Chemistry_Survey.docx) Codes for analysis, definitions, and exemplars (Codes_for analysis,_definitions,_and exemplars.docx) The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.9b00505.

Models in Chemistry Survey (PDF, DOCX)

Codes, definitions, and exemplars for model characteristics coding scheme adapted from White et al. (2011) and Pluta et al. (2011) and inductive codes; used for analysis of reasoning on both domain-general and model-specific (PDF, DOCX)

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: nicole-becker@uiowa.edu.

ORCID

Katherine Lazenby: 0000-0002-9672-8631
Nicole M. Becker: 0000-0002-1637-714X

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation under grant DUE-1611622 and the National Science Foundation Graduate Research Fellowship Program under Grant No. 1650114. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

■ REFERENCES

(1) Johnstone, A. H. Why Is Science Difficult to Learn? Things Are Seldom What They Seem. *J. Comput. Assist. Learn.* **1991**, *7*, 75−83.

(2) Schwarz, C. V.; Passmore, C.; Reiser, B. J. *Helping Students Make Sense of the World Using Next Generation Science and Engineering Practices*; National Science Teachers' Association Press: Arlington, VA, 2016.

(3) Harrison, A. G.; Treagust, D. F. A Typology of School Science Models. *Int. J. Sci. Educ.* **2000**, *22*, 1011−1026.

(4) Schwarz, C. V.; White, B. Y. Metamodeling Knowledge: Developing Students' Understanding of Scientific Modeling. *Cogn. Instr.* **2005**, *23*, 165−205.

(5) Holme, T.; Murphy, K. The ACS Exams Institute Undergraduate Chemistry Anchoring Concepts Content Map I: General Chemistry. *J. Chem. Educ.* **2012**, *89*, 721−723.

(6) Holme, T.; Luxford, C.; Murphy, K. Updating the General Chemistry Anchoring Concepts Content Map. *J. Chem. Educ.* **2015**, *92*, 1115−1116.

(7) Lazenby, K.; Rupp, C. A.; Brandriet, A.; Mauger-Sonnek, K.; Becker, N. Undergraduate Chemistry Students' Conceptualization of Models in General Chemistry. *J. Chem. Educ.* **2019**, *96*, 455−468.

(8) Lazenby, K.; Stricker, A.; Brandriet, A.; Rupp, C. A.; Mauger-Sonnek, K.; Becker, N. M. Mapping Undergraduate Chemistry Students' Epistemic Ideas about Models and Modeling. *J. Res. Sci. Ed.* **2020**.

(9) Brandriet, A.; Rupp, C. A.; Lazenby, K.; Becker, N. Evaluating Students' Abilities to Construct Mathematical Models from Data Using Latent Class Analysis. *Chem. Educ. Res. Pract.* **2018**, *19*, 375−391.

(10) Becker, N.; Rupp, C. A.; Brandriet, A. Engaging Students in Analyzing and Interpreting Data to Construct Mathematical Models: An Analysis of Students' Reasoning in a Method of Initial Rates Task. *Chem. Educ. Res. Pract.* **2017**, *18*, 798−810.

(11) National Research Council. *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*; The National Academies Press: Washington, DC, 2012.

(12) Tien, L. T.; Rickey, D.; Stacy, A. M. The MORE Thinking Frame: Guiding Students' Thinking in the Laboratory. *J. Coll. Sci. Teach.* **1999**, *28*, 318−324.

(13) Hestenes, D. Toward a Modeling Theory of Physics Instruction. *Am. J. Phys.* **1987**, *55*, 440−454.

(14) Windschitl, M.; Thompson, J.; Braaten, M. Beyond the Scientific Method: Model-Based Inquiry as a New Paradigm of Preference for School Science Investigations. *Sci. Educ.* **2008**, *92*, 941−967.

(15) DeBoer, G. E. *A History of Ideas in Science Education: Implications for Practice.*; Teachers College Press: New York, 1991.

(16) National Research Council. *National Science Education Standards*; National Academies Press: Washington, DC, 1996.

(17) Osborne, J. Teaching Scientific Practices: Meeting the Challenge of Change. *J. Sci. Teach. Educ.* **2014**, *25*, 177−196.

(18) Ford, M. 'Grasp of Practice' as a Reasoning Resource for Inquiry and Nature of Science Understanding. *Sci. Educ.* **2008**, *17*, 147−177.

(19) Brewe, E.; Sawtelle, V.; Kramer, L. H.; O'Brien, G. E.; Rodriguez, I.; Pamelá, P. Toward Equity through Participation in Modeling Instruction in Introductory University Physics. *Phys. Rev. Spec. Top.-Phys. Educ. Res.* **2010**, *6*, 010106.

(20) Jackson, J.; Dukerich, L.; Hestenes, D. Modeling Instruction: An Effective Model for Science Education. *Sci. Educator* **2008**, *17*, 10−17.

(21) Brewe, E.; Kramer, L.; O'Brien, G. Modeling Instruction: Positive Attitudinal Shifts in Introductory Physics Measured with CLASS. *Phys. Rev. Spec. Top.-Phys. Educ. Res.* **2009**, *5*, 013102.

(22) Wang, J.; Guo, D.; Jou, M. A Study on the Effects of Model-Based Inquiry Pedagogy on Students' Inquiry Skills in a Virtual Physics Lab. *Comput. Hum. Behav.* **2015**, *49*, 658−669.

(23) Rickey, D.; Stacy, A. M. The Role of Metacognition in Learning Chemistry. *J. Chem. Educ.* **2000**, *77*, 915−920.

(24) McPadden, D.; Brewe, E. Impact of the Second Semester University Modeling Instruction Course on Students' Representation Choices. *Phys. Rev. Phys. Educ. Res.* **2017**, *13*, 020129.

(25) Tien, L. T.; Teichert, M. A.; Rickey, D. Effectiveness of a MORE Laboratory Module in Prompting Students to Revise Their Molecular-Level Ideas about Solutions. *J. Chem. Educ.* **2007**, *84*, 175−181.

(26) Berland, L. K.; Schwarz, C. V.; Krist, C.; Kenyon, L.; Lo, A. S.; Reiser, B. J. Epistemologies in Practice: Making Scientific Practices Meaningful for Students. *J. Res. Sci. Teach.* **2016**, *53*, 1082−1112.

(27) Pluta, W. J.; Chinn, C. A.; Duncan, R. G. Learners' Epistemic Criteria for Good Scientific Models. *J. Res. Sci. Teach.* **2011**, *48*, 486−511.

(28) Schwarz, C. V.; Reiser, B. J.; Davis, E. A.; Kenyon, L.; Achér, A.; Fortus, D.; Shwartz, Y.; Hug, B.; Krajcik, J. Developing a Learning Progression for Scientific Modeling: Making Scientific Modeling Accessible and Meaningful for Learners. *J. Res. Sci. Teach.* **2009**, *46*, 632−654.

(29) White, B. Y.; Collins, A.; Frederiksen, J. R. The Nature of Scientific Meta-Knowledge. In *Models and Modeling: Cognitive Tools for Scientific Enquiry*; Khine, M. S., Saleh, I. M., Eds.; Springer Netherlands: Dordrecht, 2011; pp 41−76.

(30) Greene, J. A.; Yu, S. B. Educating Critical Thinkers: The Role of Epistemic Cognition. *Policy Insights Behav. Brain Sci.* **2016**, *3*, 45−53.

(31) Erduran, S.; Jiménez-Aleixandre, M. P. *Argumentation in Science Education.*; Springer Netherlands: Dordrecht, 2008.

(32) Sandoval, W. A.; Reiser, B. J. Explanation-Driven Inquiry: Integrating Conceptual and Epistemic Scaffolds for Scientific Inquiry. *Sci. Educ.* **2004**, *88*, 345−372.

(33) Schuchardt, A. M.; Schunn, C. D. Modeling Scientific Processes with Mathematics Equations Enhances Student Qualitative Conceptual Understanding and Quantitative Problem Solving. *Sci. Educ.* **2016**, *100*, 290−320.

(34) Gobert, J. D.; Pallant, A. Fostering Students' Epistemologies of Models via Authentic Model-Based Tasks. *J. Sci. Educ. Technol.* **2004**, *13*, 7−22.

(35) Brewe, E. Modeling Theory Applied: Modeling Instruction in Introductory Physics. *Am. J. Phys.* **2008**, *76*, 1155−1160.

(36) Cheng, M.-F.; Lin, J.-L. Investigating the Relationship between Students' Views of Scientific Models and Their Development of Models. *Int. J. Sci. Educ.* **2015**, *37*, 2453−2475.

(37) Chittleborough, G.; Treagust, D. F. The Modelling Ability of Non-Major Chemistry Students and Their Understanding of the Sub-Microscopic Level. *Chem. Educ. Res. Pract.* **2007**, *8*, 274−292.

(38) Cooper, M. M.; Stowe, R. L. Chemistry Education Research—From Personal Empiricism to Evidence, Theory, and Informed Practice. *Chem. Rev.* **2018**, *118*, 6053−6087.

(39) Hammer, D.; Elby, A. Tapping Epistemological Resources for Learning Physics. *J. Learn. Sci.* **2003**, *12*, 53−90.

(40) Grosslight, L.; Unger, C.; Jay, E.; Smith, C. L. Understanding Models and Their Use in Science: Conceptions of Middle and High School Students and Experts. *J. Res. Sci. Teach.* **1991**, *28*, 799−822.

(41) Krell, M.; Krüger, D. University Students' Meta-Modelling Knowledge. *Res. Sci. Technol. Educ.* **2017**, *35*, 1−13.

(42) Gobert, J. D.; O'Dwyer, L.; Horwitz, P.; Buckley, B. C.; Levy, S. T.; Wilensky, U. Examining the Relationship Between Students' Understanding of the Nature of Models and Conceptual Learning in Biology, Physics, and Chemistry. *Int. J. Sci. Educ.* **2011**, *33*, 653−684.

(43) Krell, M.; Reinisch, B.; Krüger, D. Analyzing Students' Understanding of Models and Modeling Referring to the Disciplines Biology, Chemistry, and Physics. *Res. Sci. Educ.* **2015**, *45*, 367−393.

(44) Treagust, D. F.; Chittleborough, G.; Mamiala, T. L. Students' Understanding of the Role of Scientific Models in Learning Science. *Int. J. Sci. Educ.* **2002**, *24*, 357−368.

(45) Crawford, B.; Cullin, M. Dynamic Assessments of Preservice Teachers' Knowledge of Models and Modelling. In *Research and the Quality of Science Education*; Boersma, K., Goedhart, M., de Jong, O., Eijkelhof, H., Eds.; Springer Netherlands: Dordrecht, Netherlands, 2005; pp 309−323.

(46) Danusso, L.; Testa, I.; Vicentini, M. Improving Prospective Teachers' Knowledge about Scientific Models and Modelling: Design and Evaluation of a Teacher Education Intervention. *Int. J. Sci. Educ.* **2010**, *32*, 871−905.

(47) Elby, A.; Hammer, D. Epistemological Resources and Framing: A Cognitive Framework for Helping Teachers Interpret and Respond to Their Students' Epistemologies. *Pers. Epistemol. Classr. Theory Res. Implic. Pract.* **2010**, 409−434.

(48) Jiménez-Aleixandre, M. P.; Bugallo Rodríguez, A.; Duschl, R. A. Doing the Lesson" or "Doing Science": Argument in High School Genetics. *Sci. Educ.* **2000**, *84*, 757−792.

(49) Brown, T. L.; Lemay, H. E., Jr.; Bursten, B. E.; Murphy, C. J.; Woodward, P. M. *Chemistry: The Central Science 12th ed.*; Pearson Education, Inc.: Upper Saddle River, NJ, 2012.

(50) Livescribe. Livescribe Smartpens; 2017. https://www.livescribe.com/en-us/smartpen/ (accessed October 18, 2019).

(51) American Educational Research Association; American Psychological Association; National Council on Measurement in Education. *Standards for Educational and Psychological Testing*; American Educational Research Association: Washington, DC, 2014.

(52) Qualtrics, L. Welcome to the New Qualtrics; 2017. https://www.qualtrics.com/support/explore-the-new-qualtrics/ (accessed October 18, 2019).

(53) Glaser, B. G. The Constant Comparative Method of Qualitative Analysis. *Soc. Probl.* **1965**, *12*, 436−445.

(54) Kirilenko, A. P.; Stepchenkova, S. Inter-Coder Agreement in One-to-Many Classification: Fuzzy Kappa. *PLoS One* **2016**, *11*, No. e0149787.

(55) Cohen, J. A Coefficient of Agreement for Nominal Scales. *Educ. Psychol. Meas.* **1960**, *20*, 37−46.

(56) Landis, J. R.; Koch, G. G. The Measurement of Observer Agreement for Categorical Data. *Biometrics* **1977**, *33*, 159−174.

(57) Talanquer, V. Explanations and Teleology in Chemistry Education. *Int. J. Sci. Educ.* **2007**, *29*, 853−870.

(58) Upmeier zu Belzen, A.; Krüger, D. Modellkompetenz Im Biologieunterricht. *Z. Für Didakt. Naturwissenschaften* **2010**, *16*, 41−57.

(59) Gilbert, J. K.; Treagust, D. *Multiple Representations in Chemical Education*; Springer Netherlands: Dordrecht, 2009; Vol. *4*.

(60) Sabella, M. S.; Redish, E. F. Knowledge Organization and Activation in Physics Problem Solving. *Am. J. Phys.* **2007**, *75*, 1017−1029.

(61) Stamovlasis, D.; Papageorgiou, G.; Tsitsipis, G. The Coherent versus Fragmented Knowledge Hypotheses for the Structure of Matter: An Investigation with a Robust Statistical Methodology. *Chem. Educ. Res. Pract.* **2013**, *14*, 485−495.

(62) Krell, M.; Upmeier zu Belzen, A.; Krüger, D. Students' Levels of Understanding Models and Modelling in Biology: Global or Aspect-Dependent? *Res. Sci. Educ.* **2014**, *44*, 109−132.

(63) Birenbaum, M.; Tatsuoka, K. K.; Gutvirtz, Y. Effects of Response Format on Diagnostic Assessment of Scholastic Achievement. *Appl. Psychol. Meas.* **1992**, *16*, 353−363.

(64) Dudycha, A. L.; Carpenter, J. B. Effects of Item Format on Item Discrimination and Difficulty. *J. Appl. Psychol.* **1973**, *58*, 116−121.

(65) Hohensinn, C.; Kubinger, K. D. Applying Item Response Theory Methods to Examine the Impact of Different Response Formats. *Educ. Psychol. Meas.* **2011**, *71*, 732−746.

(66) Disessa, A. Knowledge in Pieces. In *Constructivism in the Computer Age*; Forman, G., Pufall, P., Eds.; Lawrence Erlbaum: Hillsdale, NJ, 1988; pp 49−70.

(67) Levrini, O.; Disessa, A. A. How Students Learn from Multiple Contexts and Definitions: Proper Time as a Coordination Class. *Phys. Rev. Phys. Educ. Res.* **2008**, *4*, 010107.