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Introducing a Culture of Modeling To Enhance Conceptual Understanding in High School Chemistry Courses

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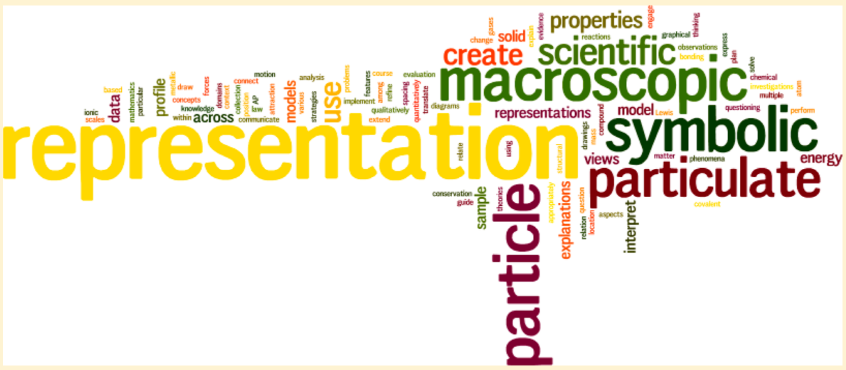
Ⓢ *Supporting Information*



ABSTRACT: Both the Next Generation Science Standards (NGSS) and the new AP Chemistry curriculum focus on a deeper understanding of content, as well as application of concepts within science classes. A well accepted research-based method for improving student understanding and the ability to apply many of the abstract concepts presented in chemistry is through the use of conceptual modeling. The lesson detailed is intended to be used in pre-AP chemistry classes at onset of the course to introduce students to ideas and vocabulary related to conceptual models and modeling so that by the time the student reaches the AP course the process of modeling would be a routine skill. This lesson involves the use of a pretest to gauge student understanding of and misconceptions about modeling, an activity to introduce vocabulary surrounding models and allow students the opportunity to create and assess a conceptual model, and a post-test to evaluate student growth in understanding the modeling practice.

KEYWORDS: *Introductory High School Chemistry/First-Year Undergraduate/General, Curriculum, Collaborative/Cooperative Learning, Inquiry-Based/Discovery Learning*

The traditional method for teaching chemistry remains very teacher-centered in many high school classrooms. Under this method, the instructor introduces and highlights concepts within a topic of study under the assumption that all students equally understand and are equally able to master the content in the same amount of time.[1] Teachers often use analogies or visual representations to aid in teaching specific content in the chemistry classroom.[2] Analogies and representations are conceptual models whose intended use is to enlighten students about some aspect of the content under study by describing the phenomenon, object, or process and/or by "providing explanations and predictions"[2] of what is being modeled. Teachers commonly employ specific models and analogies which represent their own best understanding of the concept[3] without explaining to students that these teaching tools have inherent strengths and limitations.[2−11] Because of this approach, students too often arrive in the AP Chemistry course with the assumption that understanding in chemistry can only be developed from teacher and/or textbook provided representations. Additionally, students have little to no experience/practice with skills necessary for generating, evaluating, or revising their own models.[2−7,10−13] Additional practice would create a student-centered approach to learning and might lead to students developing higher order thinking skills.

With the advent of the Conceptual Framework for K−12 Science Education[14] and the Next Generation Science Standards (NGSS),[15] science classrooms are beginning to deliberately focus on the practices of science and the behaviors of scientists over rote memorization and drill-and-practice techniques.[9] New standards and conceptual frameworks require students to take a more active role in learning and provide the opportunity to redirect teaching and learning. A shift toward student-centered techniques allow for a problem-solving based exploration of information that allows students to gain proficiency in the analysis, synthesis, and evaluation levels of Bloom's taxonomy.[16] Much of this shift in focus is due to the

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fact that the past two decades have witnessed curricular revisions that place increasing emphasis on the use of conceptual models as tools for teaching chemistry.[2,3,8−11,16−18]

The recent revision to the AP Chemistry curriculum create better alignment between the AP Chemistry learning objectives and the new set of science standards. The NGSS, which emphasize the big ideas of Chemistry and key scientific practices, and new AP curriculum call for the chemistry course to focus on a more student-centered learning environment. This student-centered learning environment is created when teachers allow students to generate and discuss their conceptual understanding, often derived through the interpretation of models, graphs, and diagrams, as well as other scientific practices like planning and carrying out investigations and engaging in argumentation from evidence. Moving toward a method of teaching which is more student-centered would provide learners with the opportunity to engage in inquiry-based activities and laboratories that better exemplify how scientists in the field approach solving a problem. These opportunities will allow students to gain experience and practice with model making, problem-solving, and methods of learning that require critical thinking, as well as to build skills needed to evaluate and interpret data on their own. An increased focus of model-based instruction in science courses to achieve these new standards may lead to students who better fit the NGSS idea of a successful science student: one who is interested in a subject, is competitive with students in the subject from around the world, and is prepared to join the workforce.[19]

As more teachers place an emphasis on conceptual models to illustrate scientific phenomena and further student understanding, they are finding readily made activities and lessons related to the creation of a model to be scarce. A few lessons and activities based on using models and modeling techniques to teach concepts in chemistry are exemplified by articles in this *Journal*'s Advanced Placement Chemistry Special Issue.[9,18] Additionally, many teachers have limited understanding of models themselves or lack training in how to introduce, discuss, and use models with their students.[2,3] Because of this, students have little to no knowledge of vocabulary associated with modeling in chemistry, how to represent matter in a model, how to interpret a model, or recognize the strengths and weaknesses of a model. Introducing modeling into the second year (AP) chemistry course often fails to allow students time to develop skills needed to accurately use a conceptual model and understand the nuances of the model at the level required on the AP Chemistry exam. By establishing the importance of modeling in pre-AP coursework, students develop an enhanced ability to use logic and reason when viewing and reviewing pictures, diagrams, and other forms of conceptual models. This extra time to develop a clearer understanding of the appropriate uses of conceptual models can serve as a tool to ensure a greater conceptual understanding of chemistry content.[2−4,7,8,12,13]

■ LITERATURE REVIEW

A conceptual model can be exemplified by a physical object such as a globe or a diagram of the nervous system in a human. These physical models aid in the learner's understanding by changing the scale of the actual concept under study while allowing details and the most important principles of the concept to be discussed.[5] Conceptual models, however, are not limited to objects representing a concept that is too large or small to be observed with the human eye.[5] Models can illustrate ideas through the use of words, gestures, formulas, prototypes, simulations, and diagrams.[4,5] In chemistry, models are most often represented in three domains: the macroscopic, symbolic, and particulate level of understanding.[20] Johnstone[20] discusses the use of these three domains in chemistry specifically, and notes that all branches of science incorporate a similar set of three domains to help learners interpret ideas and observations related to a particular concept. Coll and Lajium[3] extensively reviewed literature and determined that teachers often put little thought into which models they present to their students, how consistently they use technical vocabulary to help explain models, or how likely students will be able to follow a particular model used as an explanation of a phenomenon. Grosslight, Unger, Jay and Smith[5] categorize what can be modeled (e.g., objects or abstractions) and how models can be used (e.g., for communication, to observe, in making predictions, etc.). De Jong, Blonder, and Oversby[2] highlight that using a model from any of these categories provide opportunities for students to form misconceptions about how the models relates to the content. Proper teacher training may limit/prevent student misconceptions when using models.[3]

Ideas for addressing the NGSS and new AP curriculum through a student-centered learning environment do exist, but may not be well-known to many educators as of yet. The creation of a model often begins with fact gathering and evaluation which lead to a mental or concrete model that will be tested and most likely revised.[1] Many researchers see a correlation between the process of scientific inquiry in the laboratory and the thought processes linked to creating, testing, and communicating models.[19] This correlation allows the science teacher to create an analogy between the process of modeling and of the most frequently taught topic of science to students in grades ranging from middle school through college-the scientific method.[20] The learning outcome of teaching the scientific method in its current form year after year emphasizes the testing of predictions rather than creation of ideas.[20] This results in learners who become focused on the progression of steps at the expense of deep subject matter understanding, and lacks epistemic framing relevant to the discipline.[20] However, by using the scientific method as a foundational cornerstone, the teacher may now introduce the idea of modeling and the skills required to create, evaluate, revise, and communicate a model.

Overall, the goals of modeling practice with students is clear: to create more student-centered learning opportunities that contribute to a deeper understanding and mastery of the content under study while mimicking how scientists approach solving problems and doing chemistry. The most important outcomes from the use of models and this model-based instruction are the production of successful predictions of how matter will behave under a range of circumstances.[19] These conceptual understandings of chemical phenomena at the particulate level are specific learning objectives and interconnected science practices listed in the AP Chemistry Course and Exam Description guide.[18,21]

For those wishing to fully embrace the NGSS and College Board's interest in focusing on conceptual understanding using models, an entire model-based curriculum was developed by Arizona State University in the mid-1990s to allow science to be taught with model-based techniques that requires students to engage in scientific debate, analyze information, and construct their own pathways to learning new material.[6] Ready-made activities using models to teach science concepts, though possibly easy for the teacher to implement, are not without

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their own set of problems. Often, the concepts presented in the chemistry classroom are abstract, meaning that students will have great difficulty assimilating new ideas into their long-term memory because they have no tangible or concrete example to which to link the new information.[22] Due to teachers' inexperience with communicating scientific concepts accurately and effectively to students through the use of models, teachers often face many issues when incorporating models into their teaching.[20] Additionally, teachers often explain models or scientific phenomenon using a "multilevel thought" process that incorporates aspects from the tangible, visible environment (macroscopic) and mixes it with symbols that represent the unseen (symbolic) as well as behaviors of matter at the submicro level (particulate).[20] A common observation is that teachers move quickly into and out of these different levels that they can merge them into one "reality". This ability is truly an acquired skill based on experience and deep understanding of the content, an ability students lack and that often leads to students expressing being overwhelmed or confused by chemistry instruction, especially when models or analogies are used.

For the pre-AP and AP Chemistry teacher, Johnstone's along with De Jong, Blonder, and Oversby's works set the foundation for how to think about issues that should be addressed in effectively designing curriculum materials. Much research exists to demonstrate the positive outcomes of using model-based learning in the classroom and creating students who can approach science concepts with a modeling frame of mind. One crucial piece of information missing for the science teacher is how such instruction methods can be initially introduced to students to set a foundation upon which further study, practice, and experience will lead to the development of the knowledge and ability now called for by both the NGSS and AP curriculum.

One goal of the lesson presented in this article is to provide the teacher with a ready-made and tested lesson that can be used to introduce the concept of modeling and the vocabulary associated with it to students. More importantly, the lesson is designed to provide a mechanism by which to impact student learning. The overarching goals of the lesson itself are, first, to provide a meaningful introduction to the idea of the scientific practice of modeling to chemistry students, next, to establish a modeling skill set (i.e., the ability to create and refine a model and to recognize strengths and weaknesses of a model) within the student, and last, to recognize the language associated with the modeling process within the pre-AP chemistry class. Such an introduction to modeling early in the coursework, and the later use of modeling as a teaching method, provides a foundation on which to build and enhance student learning outcomes in the AP Chemistry course in subsequent years.

THE CLASSROOM AND THE LESSON

Population and Classroom Descriptions

The activity presented here was included during the first month of school in an honors-level chemistry class. At this school, students enrolling in the honors course are of varying ages (15−18) and grades (10th−12th, though mainly a 50/50 mix of 10th and 11th grade) who have taken biology and advanced math courses in the high school curriculum. The honors-level class is designed to be a survey course that introduces students to concepts that will be studied more in depth in the second year AP class. The College Board's recommendation that AP Chemistry be taken only after the successful completion of a first year course[21] was taken into serious consideration for development of the course sequencing and curriculum.

Students participating in this activity represent two classes of 26 and 25 students, respectively. Although all students participated in the activity and lesson, only data collected from the 28 who returned permission forms will be analyzed. Students meet 5 days per week for a 56 min period in each class, and have been enrolled in chemistry for the entire school year.

The Lesson

For the introduction to modeling lesson, students were first given a pretest (found in the Supporting Information) to establish prior knowledge related to types of possible models, vocabulary related to modeling, limitations of models, and uses of models. Next, students brainstormed ideas regarding models on the class whiteboard. After this discussion, student groups assembled into three- or four-person groups to complete a card sorting activity outlined in Figure 1 below.

Groups are given 16 index card sized pictorial representations generated from a popular chemistry textbook.[23] A description of the representations used for this activity is found in the Supporting Information. Students are asked to arrange these representations on a triangular shaped continuum, resembling Johnstone's triangle,[20] with corners labeled "macroscopic", "particulate", and "symbolic". Definitions to these three words were not discussed by the teacher with the students at any point in the activity. Students are instructed to generate an initial model by placing the 16 representations in such a manner that the pictures were closest to the corner of the

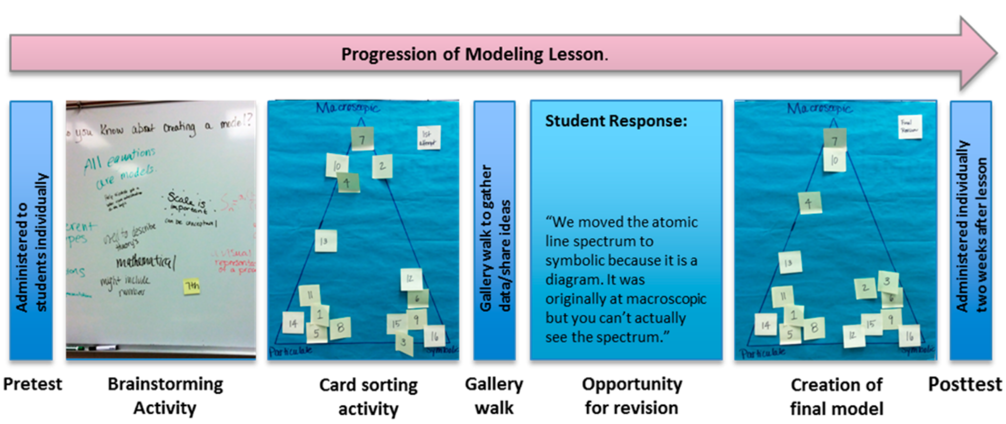

Figure 1. Progression of Modeling Lesson.

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triangle with the word that described them best. Representations that could be described using any or all of the corners of the triangle were placed at distances near the center of the triangle agreed upon by the group. This placement illustrated the group members' understanding of the most accurate relationship between the three terms in the corners and the presentation they were evaluating. Student groups were given 15 min to complete the activity.

Upon assembly of the triangle, student groups were dissolved, and students participated in a silent gallery walk in which other groups' triangles were viewed. During the gallery walk, students were asked to observe similarities and differences between their own work and that of other groups, as well as to evaluate the effectiveness of their placement of the 16 cards versus other groups' placements. Original student groups were reassembled, and students were asked to discuss their findings from the gallery walk. Groups were then asked to make revisions to their initial model based on the data they observed. Groups were allowed to change the location of any of the 16 cards they felt necessary in order to demonstrate the degree of the group's understanding of the meaning of the three terms and examples that could be used to illustrate those terms. Next, groups were tasked with completing a questionnaire in which they detailed revisions made to their original model and what prompted them to make these changes. Groups who decided not to revise their original triangle were also tasked with explaining why they made no changes.

Finally, the class was reconvened and students viewed a short presentation that allowed for discussion of vocabulary related to modeling as well as the process of creating a model. Emphasis was placed on the similarities between the use of the scientific method (hypothesis, experiment, revision of hypothesis, etc.) and the process that students had just engaged in (creation of a model, evaluation of a model, and revision of a model). Students were then introduced to the idea that the development of our understanding phenomena is based on refining an initial model.

Two weeks later the Honors Chemistry Scientific Models Quiz was given a second time, fitting the pretest/post-test format, and the results were analyzed.

■ OUTCOMES

Pretest and post-test data from free response questions 1, 2, and 3 of the Honors Chemistry Scientific Models Quiz were analyzed and coded based on criteria for models described by Grosslight et al.[5] as well as the five modes of representation described by Gilbert.[4]

The most obvious method of addressing student understanding of models was to determine students' views of what a model actually is (Table 1).

In questions 1−3, students listed examples of models to help construct their answers. In these open-ended pretest responses, students relied most heavily on examples of models, especially for answering question 1. Many students responded by identifying multiple examples within this response, so responses were coded for all possible examples per student response, not for a singular response per student. Students most commonly identified a model as a visual representation (43%) or as a mathematical formula (64%). According to Gilbert's classification of modes of models, most students exhibited an understanding of models as a concrete representation (89%) or visual representation (68%) of an object or concept in chemistry. An analysis of student responses shows that students have developed a more encompassing idea of what a model can be through the card sorting activity. Additionally, student responses became more detailed when comparing pre-/post-test responses regarding what can exemplify a model.

Data for Table 2 was collected by classifying examples students listed in their answers to questions 1−3 as either *objects* or *abstractions*. Grosslight et al.[5] explains the *object* classification by listing examples like "clothes", "airplanes", and "buildings", whereas the classification of *abstraction* was reserved for examples like "ideal behavior", "an idea (of how to build)", and "a concept or species (model of a frog...)".[5]

Table 2. Distribution of Student Answers to Modeling Pretest and Post-Test Questions 1−3, Coded To Reflect Types of Things Students Feel Can Be Modeled[5]

	Students Selecting a Classification, N = 28		
Type of Thing Modeled	Pretest, %	Post-test, %	Change, %
Object	36	21	−14
Abstraction	82	93	11

Results from the pre-/post-test indicate large increases in student knowledge that models can represent abstract concepts (13%). Student gains in vocabulary related to modeling are evidenced from the pretest to post-test administration by the student's ability to explain his meaning more effectively without relying on specific examples in the post-test answers (see Table 3).

Another important outcome generated from pre-/post-test data was in students' understanding of the relationship between the model and what it represents, as illustrated in Table 4.

Table 1. Distribution of Student Answers to Modeling Pretest and Post-Test Questions 1−3, Coded To Reflect Examples of Models[5] and Modes of Representation[4]

		Students Selecting a Classification, N = 28		
Aspect of Model Coded For	Classification of Communication Method of Model	Pretest, %	Post-test, %	Change, %
Kinds of Models[5]	Objects, etc.	36	18	−18
	Visual model	43	50	7
	Verbal	11	18	7
	Abstract	64	82	18
Modes of Representation[4]	Concrete	89	93	4
	Verbal	4	25	21
	Symbolic	21	7	−14
	Visual	68	64	−4
	Gestural	0	0	0

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Table 3. Example of One Student's Paired Responses Illustrating Growth in Vocabulary Associated with Modeling from Pretest to Post-Test Administration

Question	Sample Student **Pretest** Response	Sample Student **Post-Test** Response
1	"A scientific model is an explanation of past events or results that allow you to predict what may occur in the future. Formulas are examples of scientific models."	"A scientific model is a representation or explanation of a scientific concept or idea or even formula. They are conceptual, physical, or mathematical."
2	"Scientific models are used in explanations of teachings of different scientific concepts, scientific experiments, and in everyday life."	"Whenever a concept needs to be visually represented or explained in any way, a scientific model should be used."
3	"Scientific models are useful because they allow people to learn about concepts or facts, apply the knowledge to other concepts or ideas, and predict what may occur in the future."	"They improve understanding of abstract scientific concepts or phenomenon by creating a concrete explanation. For example, physical models help me to understand abstract ideas because I am a visual learner."

Table 4. Distribution of Student Answers to Modeling Pretest and Post-Test Questions 1−3, Coded To Reflect Students' Perception of the Relationship between a Created Model and What Is Being Modeled[5]

	Students Selecting a Relationship, N = 28		
Relationship	Pretest, %	Post-test, %	Change, %
Exactly alike	32	4	−29
Visually similar	7	46	39
Diff scale	25	21	−4
Works same	61	71	11
Other	4	0	−4

The most significant changes in student understanding are in the areas of models being exactly like the concept being represented and visually similar to it (−29% and 39%, respectively). This means that at the time of the post-test administration students realized a model was not limited to being an exact size replica of the concept it represented. Students gained understanding that models have strengths as well as limitations in that the model can lack the detail of the actual object or phenomenon and still remain a useful tool in learning chemistry. Gains in student understanding can also be noted in the notion that a model works the same as the concept or phenomenon being described. Similar to the sample response in Table 5, many students illustrated these ideas through examples of weather and making weather predictions in their responses.

Table 6 details changes in student perceptions of uses for models based most specifically on student responses to question 3 of the pre- and post-test.

The most meaningful change in student perception here is the gain in student understanding that a model can be used communicate or explain a concept or phenomenon (18%), as well as to learn and understand a concept or phenomenon (14%). These changes illustrate that students are beginning to view models and modeling beyond the level of a picture or tactile manipulative that teachers could employ to show a student during a particular lesson.

Table 6. Distribution of Student Answers to Modeling Pretest and Post-Test Questions 1−3, Coded To Reflect Students Perception of the Use of a Model[5]

Use of Model	Students Selecting a Model Use, N = 28		
	Pretest, %	Post-Test, %	Change, %
Communication/Example	64	82	18
Observe	25	29	4
Make/Build (Simulation)	21	4	−18
Learn/Understand	68	82	14
Predict	50	46	−4

■ CONCLUSIONS

This lesson on modeling provides students with an example of the thought process that goes into developing a model, as well as the opportunity to discuss the idea of a model as it relates to science practices and concepts. Through analysis of student pretest and post-test data, it is clear to see student perceptions of models and modeling have changed, as has the students' ability to describe what a model is or the uses models serve.

This single lesson does not provide enough practice with models for students to develop mastery of model creation or use, however. Instead, it serves as an introductory lesson upon which other activities and lessons can be layered as chemistry concepts and phenomena are addressed in the progression of the course. More guided practice and opportunities for generating and evaluating models are needed for students to further develop skills that would allow them to function at the levels necessary to meet the standards of the NGSS and AP Chemistry curriculum. These later activities and lessons will provide students the opportunity to synthesize models of their own, evaluate existing models, and discuss limitations in models that are currently available for a concept. Such continued exposure to modeling in the pre-AP classroom can help

Table 5. Example of One Student's Paired Responses Illustrating Growth in Perception of Uses of Models from Pretest to Post-Test Administration

Question	Sample Student **Pretest** Response	Sample Student **Post-test** Response
1	"It is a model that tries to explain a scientific observation."	"A scientific model is diagrams prototype or anything that is helpful for seeing information in a different way. A scientific model is a model for scientist to see a different perspective of science to get a better understanding."
2	"They are used all the time. They are used to explain something, they are used to prove a theory and they can be used to teach a concept."	"They are used to build tools, they are used when performing experiments, they are used to better understand a concept of science, they are used to teach other people concepts. They are used to build a prototype. They help scientists get a better picture of laws and theories."
3	"They help people understand a concept easier. It helps them visualize the concept or theory. It also helps make predictions for the future."	"They are useful because sometimes you can't just understand something right off the bat, so you make a physical or conceptual model to help understand the subject more. Also, scientific models are good for building prototypes and seeing if they work. They can use models to design a new invention and see if it actually works. Scientific models are useful for seeing science in a different perspective."

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students be more successful when they reach the AP Chemistry course.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.6b00125.

A description of the pictorial representations used to generate the 16 index cards used in this lesson's activity. (PDF)

A description of the pictorial representations used to generate the 16 index cards used in this lesson's activity. (DOCX)

The pre-/post-test questions coded for data in this lesson. (PDF)

The pre-/post-test questions coded for data in this lesson. (DOCX)

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Notes

The authors declare no competing financial interest.

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