GENERATING, EVALUATING, AND MODIFYING SCIENTIFIC MODELS USING PROJECTED COMPUTER SIMULATIONS

by Norman Price and John J. Clement

A central question for teachers is how to engage active student thinking, be responsive to student ideas, and still aim for substantial learning around specific disciplinary core ideas. These aims are especially significant in light of the *Next Generation Science Standards* (*NGSS*), which emphasize the scientific practice of generating and evaluating models (NGSS Lead States 2013. In an era of increased access to powerful computer animations and simulations, freely available on the internet, we have new opportunities to elicit and respond to student ideas.

This article describes a two-phase lesson structure (Figures 1 and 2) that uses a simulation to promote student engagement and reasoning in lessons with disciplinary core ideas for secondary school students. In phase 1, an idea-eliciting discussion, students observe a focusing event and then develop explanations and initial models without information from the teacher. This phase happens before a simulation is projected. In phase 2, a guided-modeling discussion, the projected simulation encourages students to reason about the model and to determine how they could modify and improve their initial explanations. Questions based on the images in the simulation are used to exploit complexities of the simulation as opportunities for active student reasoning.

This lesson occurs about two weeks into the Matter and Molecule curriculum (Lee et al. 1993). During lessons in the previous two weeks, students have worked on developing a particulate model of matter and describing it as composed of molecules in motion. The differences among the three states of water have been linked to the arrangement and movement of water molecules.

Lesson goal

Understanding the particulate theory of matter as outlined in *NGSS* MS-PS1: Matter and Its Interactions involves students developing a mechanistic explanation of how observable macro-phenomena can be caused by the collective, invisible dynamic action of molecules (disciplinary core idea PS1.A: Structure and Properties of Matter; NGSS Lead States 2013). The specific objective of this lesson is to have students explain the observable force of resistance as caused by the invisible action of trillions of molecules of gas bouncing against the wall of the plunger on a syringe. The guiding question of the lesson is "How does the particulate model explain the behavior of water or air when attempts are made to compress them?"

Phase 1: Idea-eliciting discussion

In this phase, as a focusing event, the teacher describes a hands-on activity and shows students the apparatus they will use in the activity (an example is described below). Students are asked to individually generate a model to predict what will happen and explain why it will happen before performing the activity or receiving content information from the teacher. Students record their prediction, results, and explanations in their notebook. Asking students to invent models to explain phenomena fosters active engagement and learning and reveals previous knowledge. After making their models, small groups of students do the activity, share their results in a whole-class discussion, listen to each other's results and ideas, and engage in scientific reasoning. During this sharing and discussion, the teacher gains diagnostic feedback on student thinking and insights into their understanding of the concept to be investigated. The teacher does not evaluate student models at this stage, since the goal is to draw out students' ideas and encourage them to clearly articulate their point of view. The ideas discussed can diverge significantly from the target model. The big challenge of the idea-eliciting discussion is for the teacher to stay neutral while attempting to comprehend, not evaluate, student models.

Specific lesson example

In this lesson, the focusing event involves the compression of gas in a closed syringe. Students are asked to explore and observe the characteristics of a liquid- and gas-filled syringe. Wearing indirectly vented chemical splash goggles, students first receive a clear, 100 mL open syringe filled with air and are asked to make a drawing of how molecules of air are distributed inside and outside of the syringe and to predict what will happen to the molecules when the syringe is compressed. Students observe the degrees of compressibility found in liquids and gases by filling their syringes with water, placing a cap tightly over the end of the syringe so nothing can escape,

FIGURE 1 Diagram of the two-phase lesson structure

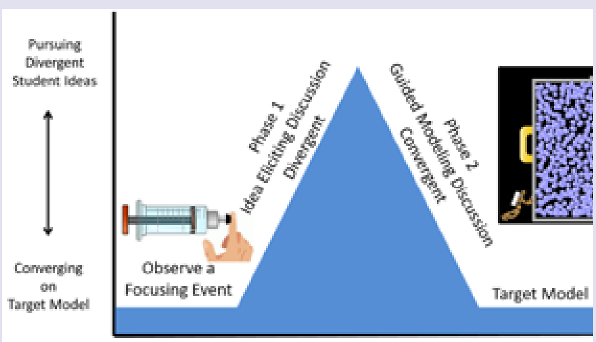

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FIGURE 2 Summary of the two-phase lesson structure using a simulation

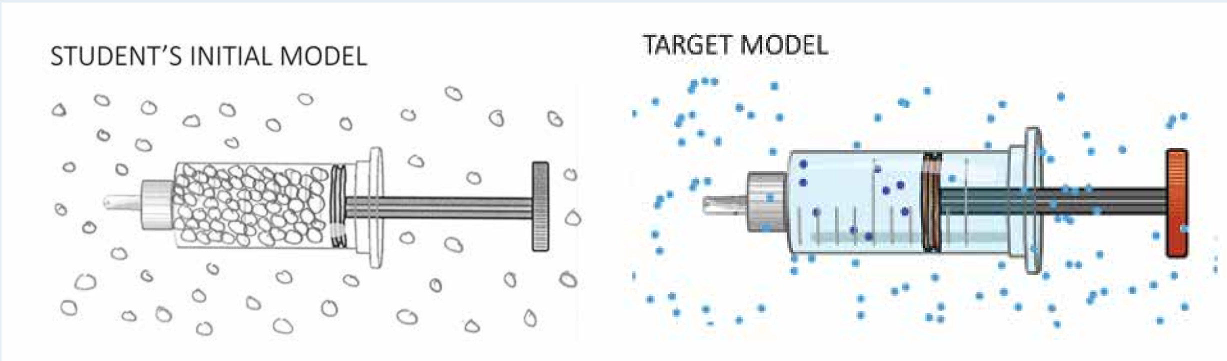
Idea-eliciting discussion: Explore divergent student thinking, before the simulation is projected.

1. Ask students to observe and discuss a focusing event.
2. Ask students to generate a model to explain the focusing event.
3. Discuss student models with a goal to understand, not evaluate, them.

Guided-modeling discussion: Converge on the target model using the simulation.

1. Orient students to the image. Situate students in the simulation.
2. Run the simulation. Highlight how the simulation represents both sides of a causal chain. Ask students to explain the link between the sides of a causal chain.
3. Pause the simulation. Ask students to predict a future state of the simulation and repeat steps 2 and 3 until students are reasoning successfully with the model.

FIGURE 3 Target and student models of molecules inside and outside of the open syringe before compression



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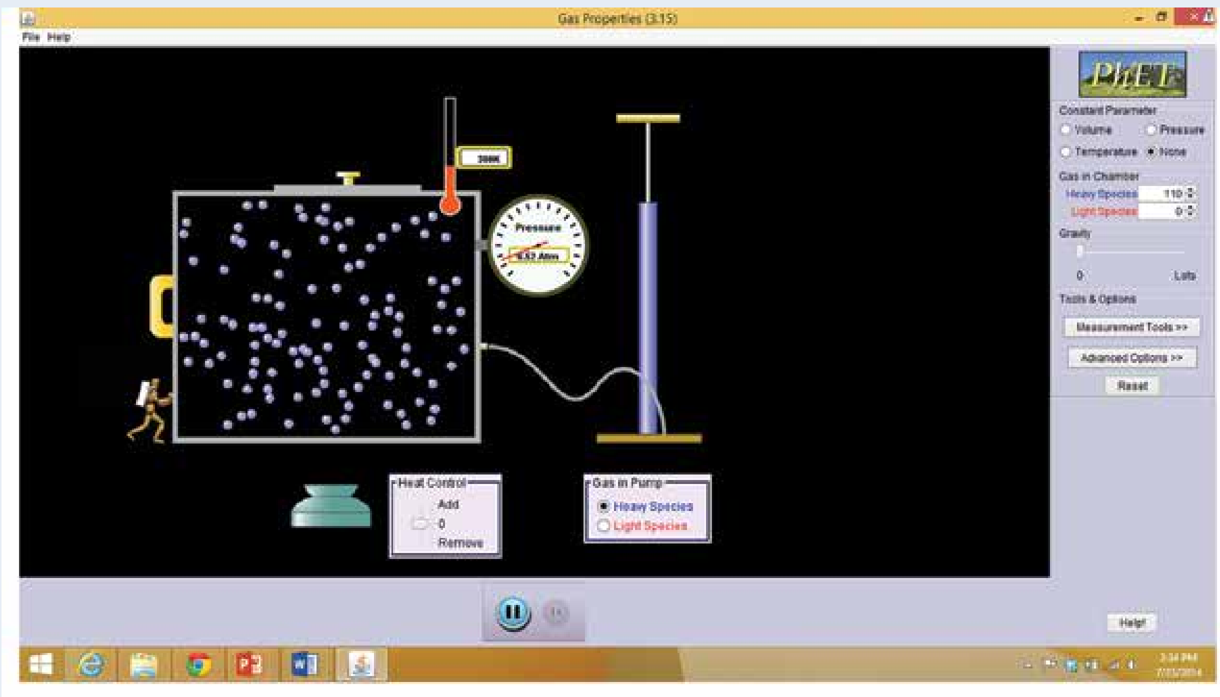
and then attempting to push the plunger inside the syringe cylinder.

They repeat this experiment with air. When students push on an air-filled syringe, they are able to squeeze about 60 mL of air down to about 15 mL. (A few students are surprised when they push enough to blow out the side of the syringe or pop off the cap. Hence the importance of students wearing safety glasses.) Students are then asked to revise their molecular model of a liquid and a gas by discussing the following questions in their notebooks: Why didn't the water-filled syringe compress but an air-filled syringe did? How can invisible air feel like a solid object when compressed?

As students work on recording the results and

FIGURE 4 Screenshot of the gas-properties simulation by PhET



(HTTP://PHET.COLORADO.EDU/EN/SIMULATION/GAS-PROPERTIES)

FIGURE 5 **Image-based questions**

These questions are asked as part of a whole-class discussion while an image is projected in front of the class. The teacher uses the questions to prompt student reasoning about the complex model images that a simulation can generate.

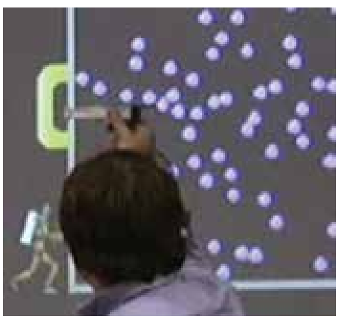
Orienting	What are we looking at?	Students and teacher identify objects in the image and map them to the situation or idea under discussion.
Situating	What if you were in the image?	Students imagine themselves in the image or as interacting with parts of it.
Highlighting	What is happening?	Students and teacher focus on conceptually important features of a cause or an effect in the image.
Linking	What is causing this?	Students and teacher focus on the link between cause and effect between elements of a complex visual.
Predicting	What will happen if...? Why?	Students predict how an image will look or behave (dynamic/function) when variables are manipulated.

revising their models, the teacher walks around the room to determine student thinking but does not attempt to correct or evaluate student responses. Some students draw air molecules compressing in an open syringe without the student pushing on the plunger (Figure 3). Discussion with students reveals that this idea is based on a preconception about the relative size of the opening in the syringe compared to the air molecules and that syringe geometry would trap the air molecules, "letting molecules come in but not let them out." Exploring divergent student ideas in a whole-class discussion fosters norms for student participation and reasoning and provides additional diagnostic feedback on the state of student models and their ability to reason with them. This 10-minute discussion is facilitated by a think-pair-share structure, which gives students with special needs a chance to discuss their reasoning in small groups before sharing their ideas with the large group.

Guided-modeling discussion

In phase 2, the guided-modeling discussion, the teacher helps students modify their models by incorporat-

FIGURE 6 **Using an orienting question to map the syringe on to the simulation**



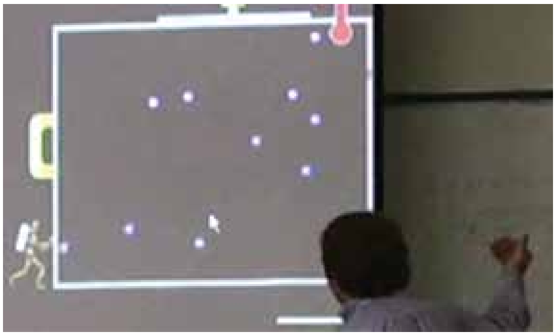
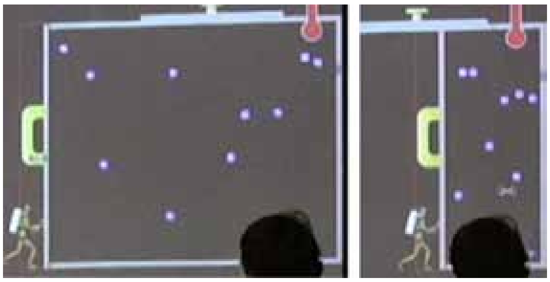
Teacher: So do you see how this simulation is like the syringe? Where's the plunger in this syringe?

Student: The little guy next to the wall.

Teacher: And so I hold the syringe up like this, and the little guy in the simulation pushes against this handled wall just like I can push against the plunger. Now what is inside the syringe? What are we able to see inside this syringe in the simulation now?

Student: Air molecules.

FIGURE 7 Highlighting by counting molecular collisions with the plunger in and out

	**Teacher:** What do you notice about the way molecules are interacting with the plunger? Count with me how many are hitting the plunger. **Student:** One... two... three... four... five... six. **Teacher:** Do you see how slowly they hit the plunger now?
	**Teacher:** Now when I push this thing in, try to count it now. **Student:** One, two, three, four, five, six…it's too fast to count! **Teacher:** It is too fast to count. So there are more hitting the plunger here when I have it compressed in like this.

ing ideas students can infer from a projected simulation (see Resource for a link to the simulation used in the specific example below). For 15 minutes, the teacher explores different segments of the particulate model of a gas by using the computer simulation's controls to pause and start the motion of the molecules and modify the variables, such as the number of molecules and size of the container holding the molecules of the gas. The simulation used here is a complex but directly observable representation of normally invisible aspects of the model.

While the simulation is a strong statement of the model, there is more to using a simulation than simply showing it. Research has demonstrated (Lowe 2003) that dynamic simulations can make greater processing demands on students than static images and that students need help determining which parts of a simulation's complex visual displays are most important. The complexity of a simulation creates a space for asking students to interpret and reason with the dynamic model represented by the simulation. Questions based on the images from the simulation are used to support student reasoning toward a convergence on the target model. Each time the simulation is modified, it provides a new projected image. In this way, the simulation serves as a reservoir of easily generated and accurate images, each representing different states of the model.

Specific example

To explain the behavior of a compressed gas, students need to understand how molecules in a gas can generate a force that can resist the force of a plunger. The PhET gas-properties simulation (available for free online; see Resource and Figure 4) depicts the invisible dynamic el-

FIGURE 8 Transcript of attempt to link cause, the push of the plunger, with effect, the motion of the molecules

Teacher: So what did I just do to the syringe?

Student: Moved it closer so all the air molecules could produce pressure.

Teacher: What did I do to the plunger first?

Student: Pushed it in.

Teacher: And what happened to those molecules then?

Student: They moved faster.

ements of the particulate model of gas. The simulation allows the teacher to pump different numbers of gas molecules into a box and see how the pressure changes when the teacher changes the box's volume. Pressure is represented by a figure pushing on the box. This simulation permits the teacher to run the model multiple times with different number of molecules and box sizes. A discussion of this simulation should develop the mental imagery of bouncing molecules and link that imagery to the force produced by a compressed gas.

Image-based questions

Image-based questions (Figure 5) support the comprehension of a simulation by focusing students' attention and reasoning on its most conceptually salient features. Orienting, situating, highlighting, linking, and predicting are categories of image-based questions that are asked in whole-class mode while the simulation is being projected in the front of the class. These questions are useful for navigating the guided-modeling discussion.

Orienting and situating

To orient students to the simulation, the teacher displays the gas-properties simulation and checks to see if students have made the connection between static simulation and the syringe. The teacher asks all students to hold up their syringe and overlay it visually on top of the image projected of the simulation. This orients students (Figure 6) to the visible and macroscopic parts of the model, namely the syringe, wall, and plunger. The teacher situates them in the simulation by suggesting that the figure in the simulation pushing on the wall is analogous to students pushing on the plunger of the syringe. The teacher then checks in to see if students understand that the dots on the screen in the simulation represent the invisible air molecules in the syringe.

Highlighting

In the exchange between the teacher and a student described in Figure 7, the teacher focuses students on conceptually important features of a cause or an effect in the image. The teacher does not emphasize the link between cause and effect but instead attempts to clarify one side of the causal chain. For example, in Figure 7, the teacher asks students to focus on, or highlight, one side of the causal chain, the molecules hitting the plunger.

Linking

The next stage of the discussion focuses on the link between cause and effect between elements of a complex visual. For example, the teacher asks students to link the behavior of molecules to the force needed to compress a syringe full of air (Figure 8). After highlighting the cause (molecules hitting the plunger) and the effect (having to push hard to keep the gas compressed), the teacher asks students to put these observations together and articulate the link between the cause and effect.

FIGURE 9 **Simulations representing extreme cases with few and many molecules**

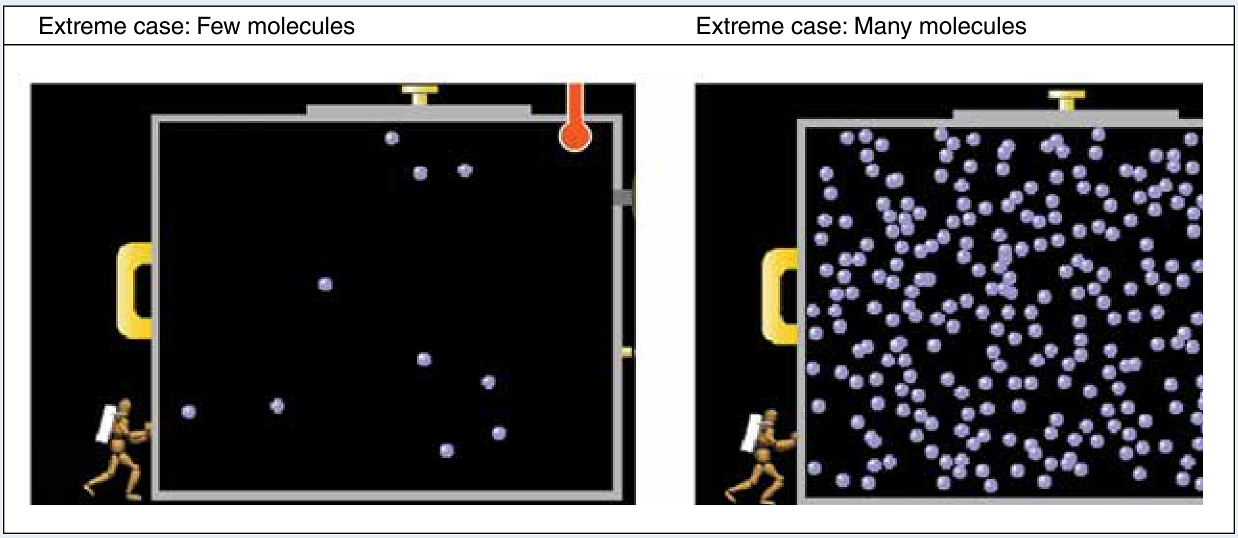
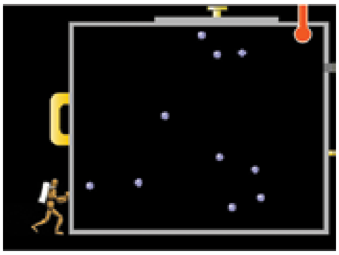
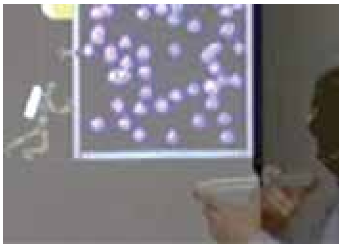


FIGURE 10 Discussion of extreme cases using highlighting and linking questions

	**Teacher:** Why isn't he pushing as hard now [when the plunger is out]? **Student:** Well, because they're not really hitting the side.
 	**Teacher:** Why is he leaning more now? [Teacher takes out syringe and starts to strain to push it in.] **Student:** [Gestures by flicking a pen] More molecules hit the wall, so that makes more pressure.

Students do the reasoning and are able make the links of the collective action of molecules and pressure.

Predicting

The next stage of the guided-modeling discussion focuses on using the simulation for making and testing predictions about how the simulation will look or behave in future situations. In this example, by changing the number of gas molecules in the chamber, the teacher could discuss two extreme cases of the syringe, one with only a few molecules and one packed full of molecules (Figure 9). While the simulation is paused, students predict how each extreme case would affect the force needed to compress the gas syringe. The teacher then uses highlighting and linking questions (Figure 5) to ask students to explain the behavior of the simulation in these two extreme cases and support their reasoning (Figure 10).

Closure and review

The teacher closes the lesson on particle motion with a review question. Students are asked to draw and describe the molecules of air in a syringe at three different points in time: an uncompressed syringe; a halfway compressed syringe; and a syringe compressed to the maximum amount they could do by hand. Students share their drawings in small groups. Finally, the teacher projects the most accurate drawings using a document camera and the class evaluates the pictures together by generating an informal rubric. The goal of this portion of the lesson is to give the teacher an opportunity to assess the student models and to provide closure to the lesson.

Conclusion

This suggested two-phase lesson (Figures 1 and 2) first explores divergent student thinking as students generate initial explanations of a focusing event and then uses a simulation to engage and support student reasoning toward a convergence on the target model. Image-based questions (Figure 5) prompt students to reason and use the simulation to evaluate and modify their model. This article describes only one lesson along a series that will be needed to get students to full

Connecting to the *Next Generation Science Standards* (NGSS Lead States 2013)

Standard **MS-PS1: Matter and its interactions**		
Performance expectation MS-PS1-4: Develop a model that predicts and describes changes in particle motion, temperature, and state of a pure substance when thermal energy is added or removed.		
Student learning previous to this lesson: Students have been introduced to the particulate model of matter, describing matter as composed of molecules in motion. The differences among the three states of water have been linked to the arrangement and movement of water molecules.		
Student learning following this lesson: After this lesson explaining the effects of compression on gases and liquids, the course will move on to developing molecular explanations for the expansion of gases, dissolving, and phase changes.		
Dimension	***NGSS* dimension code or name**	**Matching student task or question taken directly from the activity**
Disciplinary core idea	PS1.A: Structure and properties of matter	"To explain the behavior of a compressed gas, students need to understand how molecules in a gas can generate a force that can resist the force of the plunger."
Science and engineering practices	Developing and using models Constructing explanations	Before activity, students drew models to predict what would happen to molecules in a syringe during compression and then revised the models based on investigation results. Students had to explain what happened in the syringes and in the simulations.
Crosscutting concept	Cause and effect	Students were asked to use cause-and-effect relationships to predict and explain the results of the compression activity. Students had to "focus on the link between cause and effect between elements of a complex visual."

understanding of the performance expectation and the disciplinary core content.

Due to the flexibility of this specific simulation to alter variables, it is easy to obtain projected images of different states of the model, and each image gives the teacher an opportunity to discuss how the rate at which molecules collide with the plunger affects the forces on the plunger. Each time the simulation is modified, it provides a new projected image. In this way, the simulation serves as a reservoir of easily generated and accurate images, each representing different states of the model. The ability to generate multiple images makes the simulation useful for planning. Each image provided by the simulation supports the teacher with an opportunity to strategically plan sequences of the model-based questions and discussion (Figure 2).

The expanding library of free, web-based computer simulations online offers great opportunities for asking students to generate, evaluate, and modify scientific models. These lesson structures and strategies help teachers offer ways to take advantage of these modeling opportunities. ■

References

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Lowe, R.K. 2003. Animation and learning: Selective processing of information in dynamic graphics. *Learning and Instruction* 13 (2): 157–76.

NGSS Lead States. 2013. *Next Generation Science Standards: For states, by states*. Washington, DC: National Academies Press. *www.nextgenscience.org/next-generation-science-standards.*

Resource

Gas properties simulation—*http://phet.colorado.edu/en/simulation/gas-properties*

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