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Using modeling as a link to other scientific practices, disciplinary core ideas, and crosscutting concepts.

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The *Next Generation Science Standards* (*NGSS*) emphasizes content and scientific practices, but what does this actually look like in a classroom? The *NGSS* integrates scientific and engineering practices with core ideas and crosscutting concepts, merging the three dimensions from *A Framework for K–12 Science Education* (NRC 2012). By engaging themselves in science, students understand how their knowledge develops, providing "an appreciation of the wide range of approaches that are used to investigate, model, and explain the world" (NRC 2012, p. 42).

The *Framework* identifies eight scientific and engineering practices (NRC 2012). This article focuses on the practice of modeling as a tool to engage students in additional scientific practices: arguing from evidence, communicating ideas, and developing understanding of core ideas. We discuss how to support students in model building by having them develop, share, and discuss atomic models and then revise those models based on observed electrostatic interactions.

Scientific modeling

In the *NGSS,* models include physical representations, conceptual relationships among elements of a system, and simulations. These models have explanatory and predictive power, and scientists use them to generate data, explore questions, solve problems, and communicate ideas. Models are consistent with evidence, demonstrating to students that if their models do not match new evidence, they should revise or replace them (Achieve 2013; Krajcik and Merritt 2012; Schwarz et al. 2009). Figure 1 details grade-band endpoints for the modeling practice (Achieve 2013, Appendix F, p. 6).

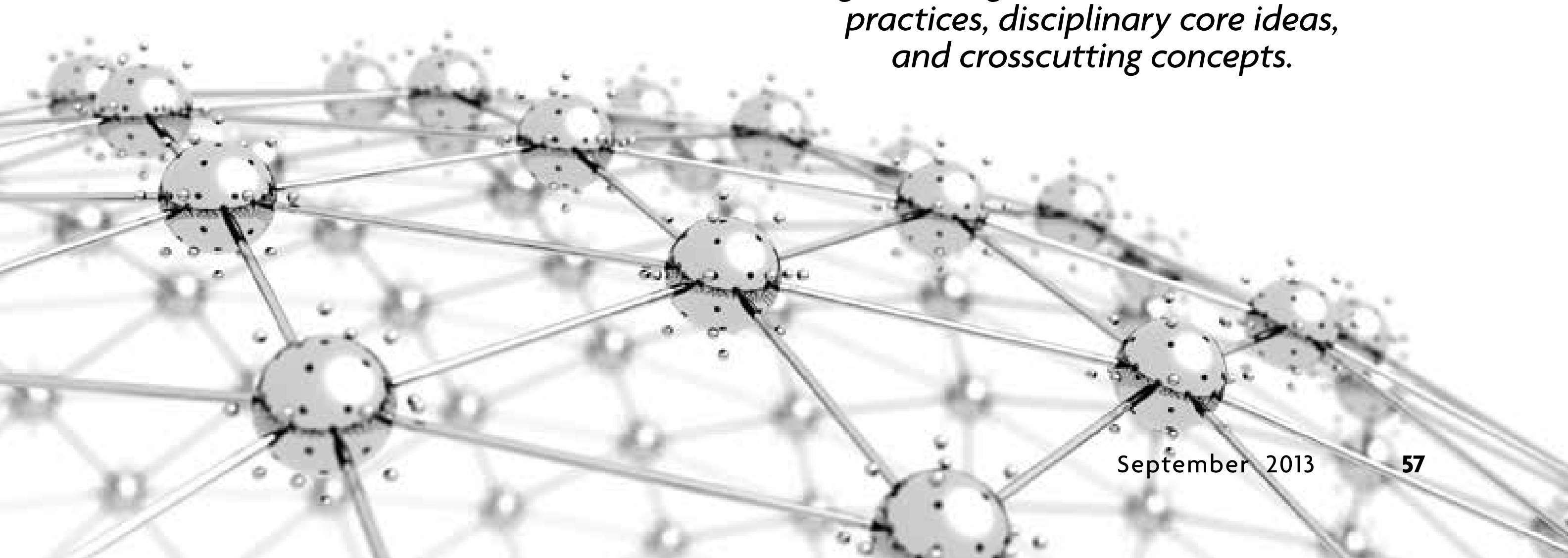
To support students' engagement in scientific practices, teachers should create an environment full of rich phenomena and meaningful data from which students build initial models. Teachers then facilitate discussions by having students share their models and ask questions, such as

- What similarities or differences exist between your models?
- How do your models highlight different aspects of the phenomenon or data?
- Can we, as a class, come to an agreement on what to include in our models?
- Which models best account for the data?

These questions require students to analyze and reflect and do not imply a "right" answer; the teacher asks probing questions and reflects students' ideas without judging responses.

Model development

To demonstrate how teachers can use modeling to support students' construction of knowledge and engagement in scientific practices, we use materials that support students in developing models of electrostatic interaction. These materials, under development as part of a National Science Foundation project (Michigan State University 2013; DRL #1232388), can explain a broad range of phenomena, forming connections among physics, chemistry, biology, and Earth science.



Phase changes, chemical reactions, protein structure and function, and the energy in hurricanes all have a foundation in electrostatic forces, a concept that can help demonstrate to students the connected nature of science. In our curricula, students construct basic models of electrostatic forces and over time—through engagement with various phenomena, computer simulations, and peer discussion—develop their models into complex frameworks for understanding inter- and intramolecular forces. As students' models evolve, they have opportunities to illustrate the evolving nature of electrostatic interactions. Teachers can also use this formative feedback to guide classroom discussions. Figure 2 depicts some of the *NGSS's* performance expectations, core ideas, scientific practices, and crosscutting concepts (Achieve 2013) related to our curricula.

Supporting argument from evidence and communication of ideas

Students start by analyzing phenomena that involve interactions between charged objects. They note patterns in how charged objects interact with each other and how charged objects interact with neutral objects. Once students realize that neutral objects attract both positively and negatively charged objects, they can begin to investigate the underlying nature of matter and atomic structure. Students use their understanding of positive and negative charges to evaluate J.J. Thomson's discovery of the electron in 1897.

Students manipulate simulations of Thomson's experiment (see "On the web") and relate their evidence to Thomson's claims that cathode rays consisted of atoms' negatively charged particles. Students then revise their atomic models to incorporate this new evidence. Figure 3 (p. 60) shows three examples of our students' responses. At this point, students know that both positive and negative particles must be present in an atom, but they have no evidence about the location of these positives and negatives. The models show no strong consensus of how charges arrange within atoms. This is an opportune moment for discussion, because displaying the models allows students to make comparisons and raise questions about the location of the charged parts of an atom.

Students next use a computer simulation of Ernest Rutherford's gold foil experiment (see "On the web") to test the distribution of charges. In 1909 Rutherford's assistants Hans Geiger and Ernest Marsden shot positively charged alpha particles at a thin sheet of gold foil and observed that although most of the alpha particles passed through the sheet without changing direction, a few deflected, and some even bounced back toward the origin. Using the simulation, students can adjust the concentration of the atom's positive charges and compare the path of the alpha particles to Rutherford's results. Students can use the simulation as a source of data about the atom's distribution of positive charges (Figure 4, p. 60).

After collecting this new data, students evaluate its impact on their atomic models. Students revise their models again, incorporating this new information (Figure 5, p. 61). Sharing their models shapes yet further revisions. These processes help students to build understanding and support their ideas by using evidence, developing communications skills, and asking questions. Students question the evidence for a particular model or claim and whether the model gives a causal account of the phenomenon. This refinement of student models mirrors the actual historical development of the modern nuclear atomic model in the early 20th century, thus allowing students to better understand the history and nature of scientific progress. Teachers can display several student-generated models

FIGURE 1

Modeling Practice Matrix From Appendix F of the *Next Generation Science Standards* (Achieve 2013).

In grades 9–12, students build on their prior experiences as they use, synthesize, and develop models to predict and show relationships among system variables and their components. To do this, students

- evaluate merits and limitations of two different models of the same proposed tool, process, mechanism, or system, selecting or revising the model that best fits the evidence or design criteria;
- design a test of a model to ascertain its reliability;
- develop, revise, or use a model to illustrate or predict the relationships among systems or components of systems;
- use multiple types of models to provide mechanistic accounts or predict phenomena and move flexibly between model types based on merits and limitations;
- create a complex model that allows for manipulation and testing of a proposed process or system; and
- develop or use a model (including mathematical and computational) to generate data to support explanations, predict phenomena, analyze systems, or solve problems.

FIGURE 2

Performance expectations (Achieve 2013).

Performance expectations represent what students can be assessed on, but they do not include how teachers help students develop understanding. Teachers can help students reach expectations by using the core ideas with a variety of practices.

HS-PS2 Motion and Stability: Forces and Interactions

Performance Expectation

Students who demonstrate understanding can:

HS-PS2-4. Use mathematical representations of Newton's law of gravitation and Coulomb's law to describe and predict the gravitational and electrostatic forces between objects.

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting concepts
Using Mathematics and Computational Thinking • Use mathematical representations of phenomena to describe explanations.	**PS2.B: Types of Interactions** • Newton's law of universal gravitation and Coulomb's law provide the mathematical models to describe and predict the effects of gravitational and electrostatic forces between distant objects • Forces at a distance are explained by fields (gravitational, electric, and magnetic) permeating space that can transfer energy through space. Magnets or electric currents cause magnetic fields; electric charges or changing magnetic fields cause electric fields.	**Patterns** • Different patterns may be observed at each of the scales at which a system is studied and can provide evidence for causality in explanations of phenomena.

Performance Expectation

Students who demonstrate understanding can:

HS-PS2-6. Communicate scientific and technical information about why the molecular-level structure is important in the functioning of designed materials.

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting concepts
Obtaining, Evaluating, and Communicating Information • Communicate scientific and technical information (e.g., about the process of development and the design and performance of a proposed process or system) in multiple formats (including orally, graphically, textually, and mathematically).	**PS2.B: Types of Interactions** • Attraction and repulsion between electric charges at the atomic scale explain the structure, properties, and transformations of matter, as well as the contact forces between material objects.	**Structure and Function** • Investigating or designing new systems or structures requires a detailed examination of the properties of different materials, the structures of different components, and connections of components to reveal its function and/or solve a problem.

and ask the class to note similarities and differences. This supports model development and revision; students can identify how different models highlight aspects of the phenomenon. Students can begin to argue in support of one model over another, raising questions that need testing before they can make decisions.

FIGURE 3

Student models of atoms.

(Note: None of the below images represent the current scientific consensus on the atom.)

The images below show three students' models that they constructed after exploring simulations of Thompson's cathode ray experiments. Though the images vary in placement of charged particles, all account for neutrality of atoms and are consistant with students' evidence. The images show that atoms have smaller positively and negatively charged particles inside them.

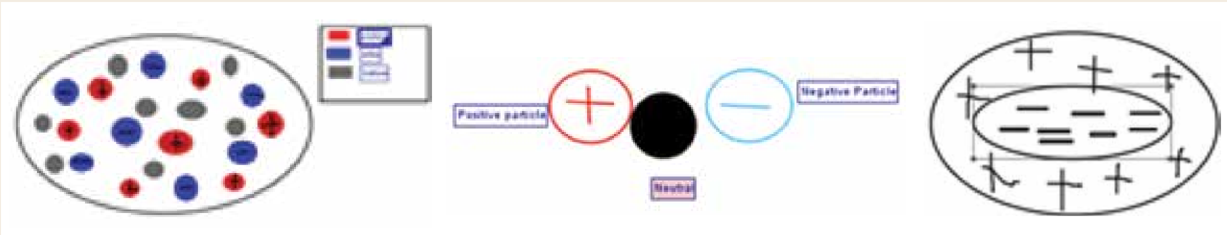
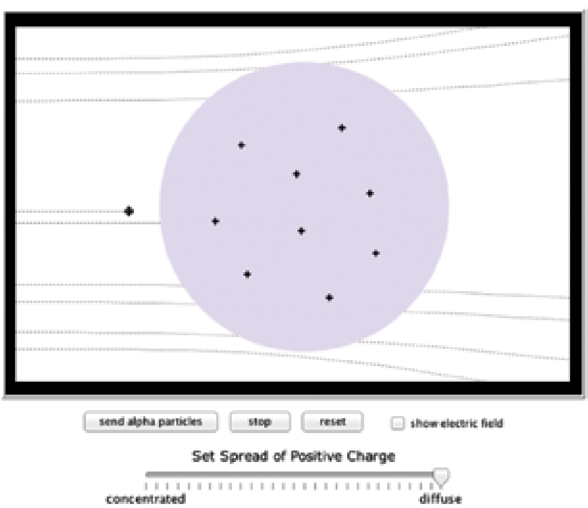
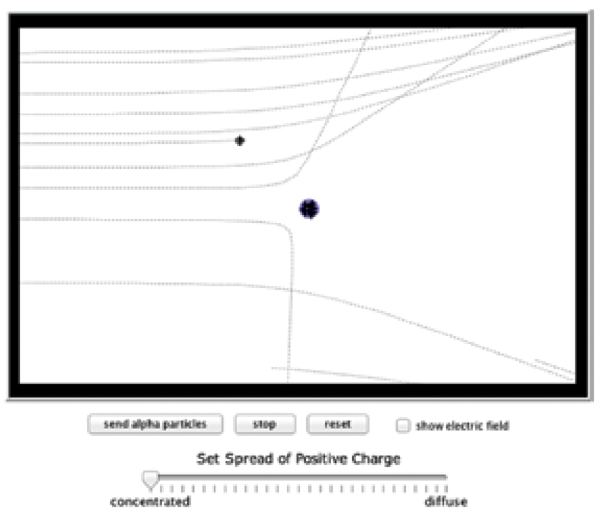


FIGURE 4

Data from a computer model of Rutherford's experiment.



In this image, the large blue area shows the distribution of positive charges, which students can manipulate. The small circle represents an alpha particle, and the lines trace the paths of these particles as they move left to right across the screen. The simulation shows that the electric field is not strong enough to cause alpha particles to significantly change direction when the positive charge is diffused. The alpha particles near the edges of the positively charged area curve slightly but do not return to the direction of origin.

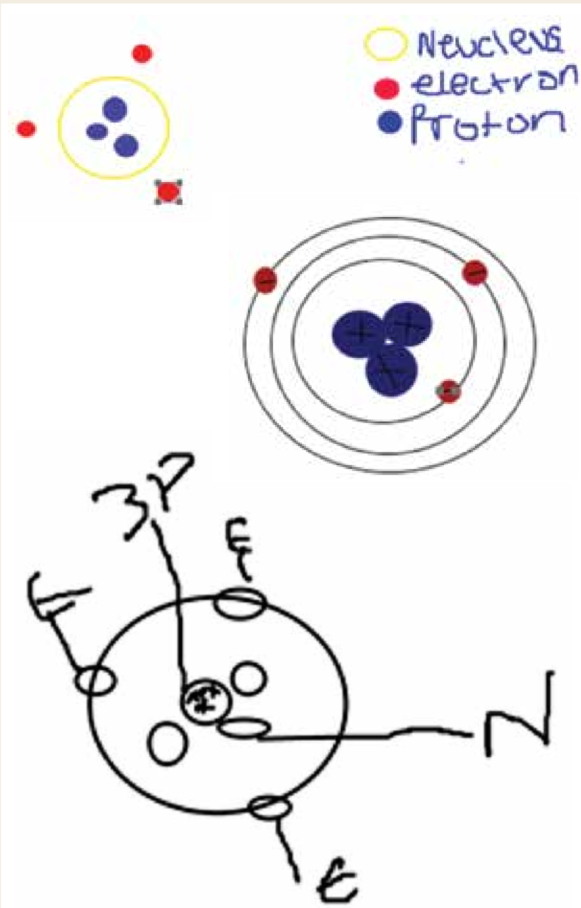


When the positive charges are concentrated, they create a strong electric field, causing significant deflection of the alpha particle. On the computer, students select "show electric field" to display arrows that represent the direction and strength of the electric field.

FIGURE 5

Students' revised atom models.

We instructed students to draw an atom with three protons. All three students show the positive charges in the middle and equal numbers of electrons and protons. We had not discussed neutrons yet, so students' models reflect this—paralleling the history of science, since the neutron was not discovered until 23 years after Ernest Rutherford's experiment. Students' revised models provide causal accounts that explain the findings from the Rutherford simulation.



We display students' revised models so they can discuss how objects become charged and explore the relationship between the number of protons and electrons and the overall charge of an atom. When asked whether the number of protons or electrons was more likely to change when something becomes electrically charged, students initially answered that both had a fair chance at change. When asked to use their models to support their answers, several students reasoned the electrons would more likely transfer between atoms because of their location on the outside part of the atom. They used their models to support their arguments.

Conclusion

Using models can help students participate in *NGSS* principles such as communicating ideas, arguing based on evidence, and developing understanding of scientific and engineering practices and core ideas. Developing and using models helps students participate in this essential scientific and engineering practice, supports other *NGSS* practices such as communicating ideas and arguing based on evidence, and develops understanding of disciplinary core ideas. Though we use modeling to teach our students about electrostatic interaction, any science class lends itself to the practice of students developing, sharing, discussing, and modifying models. Models can explain a broad range of phenomena, forming connections among physics, chemistry, biology, Earth science, and more. ■

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On the web

The Concord Consortium Molecular Workbench simulations of J.J. Thomson's experiments: *http://concord.org/tst/discovering-electrons1* and *http://concord.org/tst/discovering-electrons2*. Simulation of Ernest Rutherford's gold foil experiment: *http://concord.org/tst/rutherford-model.*

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