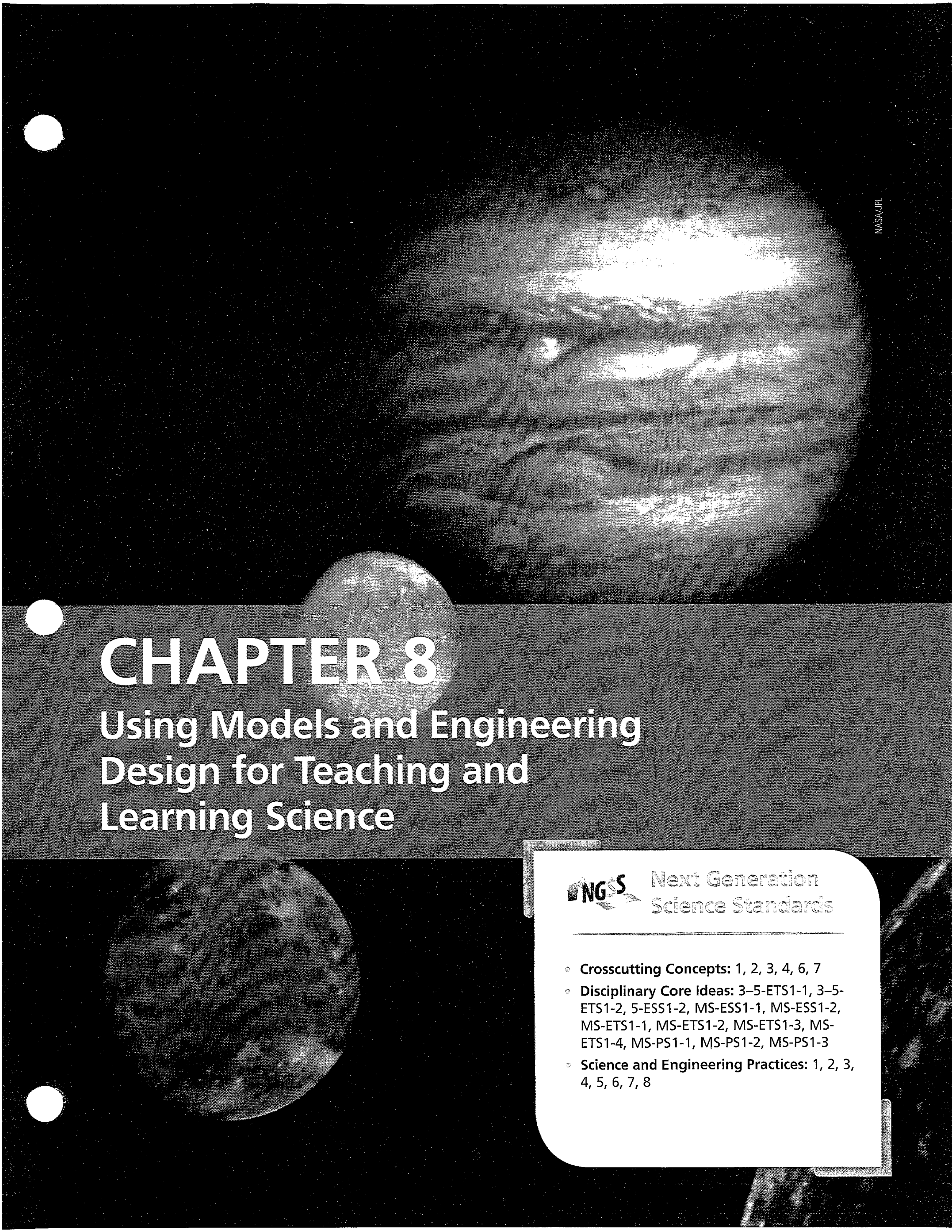


NASA/JPL

# CHAPTER 8

# Using Models and Engineering Design for Teaching and Learning Science

NGSS Next Generation Science Standards

- **Crosscutting Concepts:** 1, 2, 3, 4, 6, 7
- **Disciplinary Core Ideas:** 3–5-ETS1-1, 3–5-ETS1-2, 5-ESS1-2, MS-ESS1-1, MS-ESS1-2, MS-ETS1-1, MS-ETS1-2, MS-ETS1-3, MS-ETS1-4, MS-PS1-1, MS-PS1-2, MS-PS1-3
- **Science and Engineering Practices:** 1, 2, 3, 4, 5, 6, 7, 8

**LEARNING OBJECTIVES**

After reading this chapter, you should be able to:

- 8-1 Understand how modeling helps to explain natural phenomena.
- 8-2 Explore how a physical model of the solar system provides context for the science ideas to be learned.
- 8-3 Examine how modeling leads to meaning making.
- 8-4 Discuss how moon phase journaling can lead to models of natural phenomena.
- 8-5 Understand the connection between developing models and engineering design.
- 8-6 Analyze how a design challenge incorporates engineering practices.

## Reflection

### To Think About:

- What models have you made? Did you ever build a model airplane? A clay model? An abstract model? A computer model?
- What objects of nature require a model for direct exploration?
- How can making models facilitate learning?
- Where can you find virtual models of natural phenomena?

I have just returned from visiting the planets Mars, Jupiter, and Saturn. It was an exciting trip that revealed so many details of these planets—my, how huge Jupiter is! It took much longer to reach Jupiter from Earth than to reach Mars.

Okay, this was a virtual trip, but the views were breathtaking, and knowing I could "travel" anywhere in our solar system or the entire universe with my computer mouse was quite exciting. I was using the WorldWide Telescope available on the Internet. Replete with real images from the finest space and ground telescopes, this computer portal allows the viewer to visit real images in the solar system, the Milky Way galaxy, and beyond to other galaxies. I started on planet Earth, traveled to Mars, then Jupiter, and then on to Saturn and back to Earth. It was a quick trip in real time, but I began to get a feeling for celestial relationships: the planets that are closer to us and those that are further; those that are much bigger than ours and those that are smaller.

This computer visualization of the universe is just one type of model. This chapter explores the use of various kinds of models in science education. The activities you have been reading about in earlier chapters invite students to become directly involved with their objects of study. Sometimes, however, it is not possible to explore the objects directly. They are too large or too small, too hot or too cold, too far away, or inaccessible for other reasons. In these cases, students and teachers can use models, physical or virtual, to learn a great deal about the natural world. Additionally, developing models of phenomena that we can study directly gives us added insight into the science concepts.

## 8-1 The Usefulness of Models

When scientists are unable to work directly with materials, they construct models of them in an effort to gain a better understanding of their structure and function. A **model** may be a physical structure, either a smaller or a larger representation of a system or an object. For example, when I was in fifth grade, I made a model of a tooth for Dental Health Week in my elementary school. In order to build it, I needed to gather pictures of teeth and understand the various parts of a tooth. I had to decide which type of tooth to represent as well as figure out the size and composition of the model. What I remember most from making that tooth model—aside from my struggle to create the plaster mold out of clay—was that, to my surprise, the tooth is a complicated structure with lots of layers. In daily life we see only the crown, the visible part of a tooth.

**model**
A representation of a system or object: for example, a physical structure that imitates a smaller or larger structure, a mental construct that represents an object or process, or a computer program that parallels the workings of a larger system.

My model, though, included markings to show where the root canal, the nerve, and the pulp are.

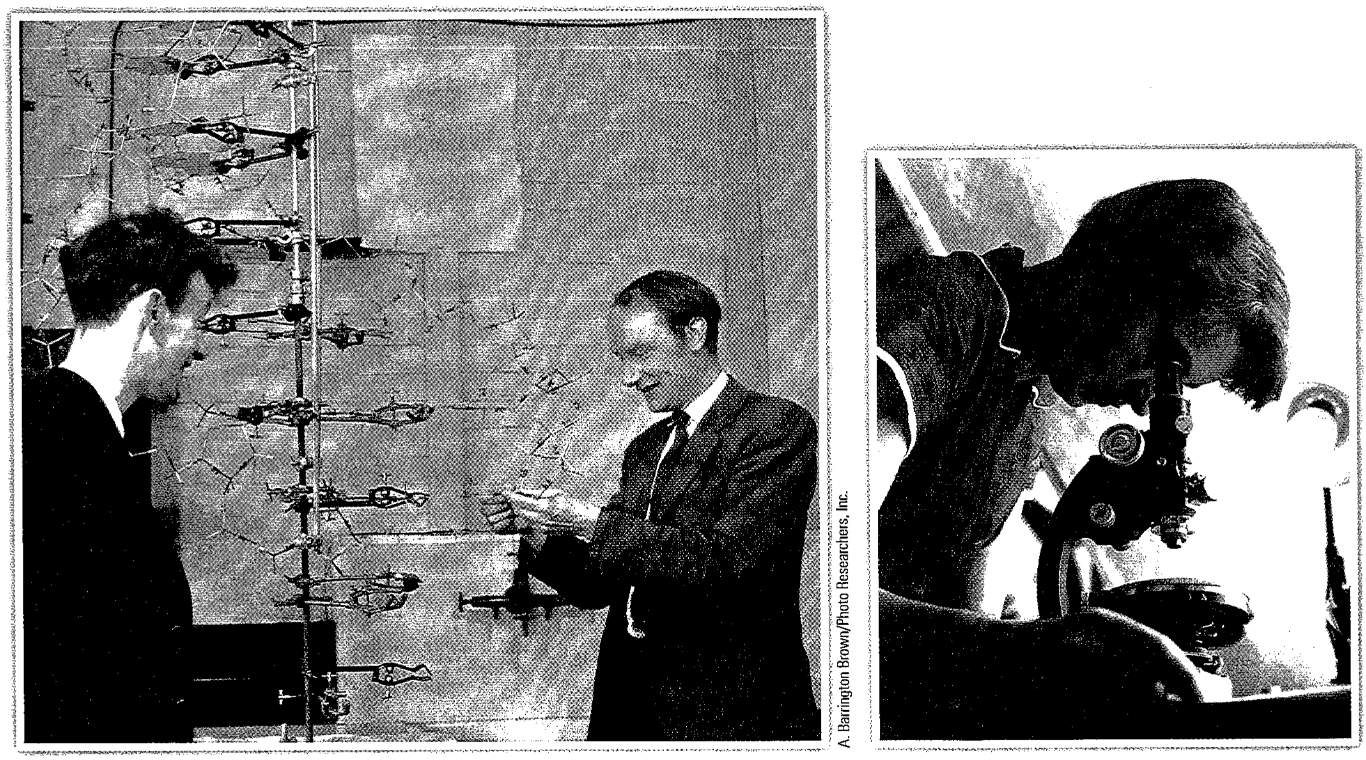
Although not exact by any means, my model tooth remained on display for all of Dental Health Week. Moreover, I never *forgot* the structure of a tooth. Decades later, when I needed to have the contents of the pulp chamber of one of my molars removed because it was infected, I pictured the root canal from my model.

Similarly, scientists have long made physical models out of whatever materials are available to them. One of the most famous models involved the chemical structure of deoxyribonucleic acid, known as DNA—the material in our cells that passes genetic information from one generation to the next. The model—developed by scientists James Watson, Francis Crick, Rosalind Franklin, and Maurice Wilkins—marked one of the most important scientific revolutions of the twentieth century and was made out of materials resembling giant tinker toys.

Scientists construct models after they have gathered enough data about their objects of study to begin to make a reasonable facsimile. In the case of DNA, the scientists used data from an x-ray crystallography method employed at the time by Rosalind Franklin. Dr. Franklin was able to gather images of patterns made by the DNA molecule when it reflected x-rays. Her data became the basis for Watson and Crick's DNA model (Photo 8.1). Unfortunately, she died before her three team members were awarded the Nobel Prize for science and medicine for their remarkable discovery.

### 8-1a What Do We Mean by a Model?

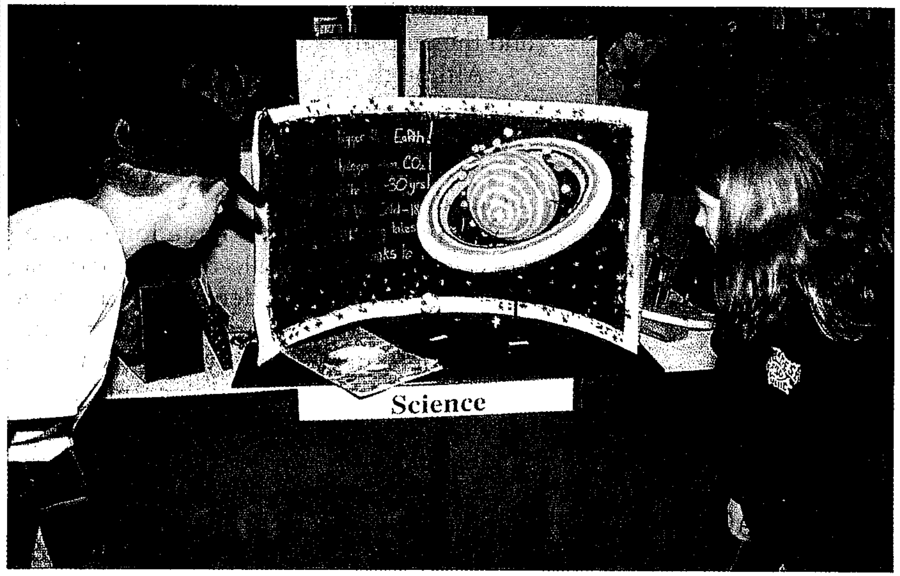
A model does not have to be something you can touch. It may be a mental construct—a design that forms an image in your mind representing a concrete process or object. For example, I carry a mental model of an atom in my mind; it is the way I have conceptualized an atom on the basis of what I have learned.



A. Barrington Brown/Photo Researchers, Inc.

Science Source/Getty Images

PHOTO 8.1 James Watson, Frances Crick, and Rosalind Franklin built a double helical model of DNA.



Tony Freeman/PhotoEdit

**PHOTO 8.2** We construct models in order to make meaning of objects that are impossible to study through direct manipulation. Students created this model of Saturn to help conceptualize their information about the planet.

Models can also be virtual, computer-generated images, or large-scale virtual constructions. The WorldWide Telescope is described as a "visualization software environment" (WorldWide Telescope, 2015). Today, a great deal of scientific research is performed by using computer models of varying degrees of complexity. As just one example, meteorologists often explore potential weather events by using computer simulations based on actual weather satellite data. You see the results of these computer models on the television news each day when forecasters describe the possible tracks a storm system may take.

## 8-2 An Edible Solar System

As you will discover from the following science stories, making models is a way of furthering your students' understandings of objects and events that they cannot manipulate directly (Photo 8.2). Model making can take place at any level of science education. First, we will see what happens when Mr. Johnston and his fifth-grade class build and explore a model of the solar system and students make drawings of orbits. Then we will see eighth graders construct models of atoms employing principles of engineering design.

## SCIENCE STORY

### An Edible Solar System

Mr. Johnston is a veteran elementary school teacher. He has a science room in a small, suburban elementary school, and students visit his room once a week with their classroom teacher. Together the students engage in science activities in Mr. Johnston's science room, which they then continue in their regular classroom. There are interesting materials on display and arranged in storage cabinets all around the room. Three hamsters, a rabbit, and numerous plants share the room with Mr. Johnston.

This particular day, when fifth graders arrive for their morning visit, the only materials Mr. Johnston has set out are round fruits and vegetables of varying sizes: grapes, peas, cabbages, grapefruits, melons of different types, apples of varying sizes, oranges, apricots, and small tomatoes.

"Are we dissecting fruits and vegetables again?" the students ask.

Mr. Johnston laughs. "No," he says. "We are going to use these fruits and vegetables to make a model of the planets in our solar system."

The students have been exploring "objects in the sky," and they have just completed a huge posterboard model of the sun, so this project makes sense to them. They are excited to begin. "How do we do it?" they ask.

Mr. Johnston explains that they need to gather a lot of information before they can use these materials to make a model. "Remember all the research we did on the sun?" he asks. "What type of information do we need about the solar system in order to construct a reasonable classroom model?"

The students brainstorm various questions to answer, including the following:

- What are all the objects in the solar system?
- How far away from Earth are the rest of the planets?
- How many moons does each planet have?
- What are the planets made of?
- How many planets have atmospheres?
- How big are the planets?
- How far away from the sun is each planet?
- What colors are the planets?
- Is Pluto a planet?

Mr. Johnston records these questions on poster paper as the students record them in their science notebooks. He invites the students to work in groups of four and to decide on the particular questions they want to research. He explains that they are in the "data-gathering" phase of this model-making project, and they must select the questions they are most interested in exploring.

At this point, Mr. Johnston also shares the story of Pluto with the class because it is an opportunity to talk about how scientists classify objects in the sky. He explains that Pluto was discovered in 1930 by the astronomer Clyde Tombaugh and was originally classified as a planet. Since that time, we have developed stronger telescopes, including the Hubble Space Telescope, and we have learned more about the outer reaches of the solar system. In 2006, as a result of our recent learning, Pluto was reclassified as a "dwarf planet" rather than a regular planet—leaving only eight planets in our solar system. Mr. Johnston invites the students to find out why. As a hint, he asks them to learn what attributes define a planet.

> ***My thinking:*** *I am impressed with the way Mr. Johnston offers important information about Pluto but does not give the class the entire story—just enough to get them interested! It is a challenge to know how much to give and how much to require of the students as the groups construct their understanding of the solar system.*

Mr. Johnston has had the WorldWide Telescope software downloaded on the science classroom laptops, and he used the website on his SMART Board to introduce the "Objects in the Sky" unit. He encourages the students to use the laptops to go on the WorldWide Telescope. Mr. Johnston assures the students that they can use this exciting resource, and he points out that they also can access other planetary websites for accurate data about the planets. Their goal, he reminds them, is to find data they need to construct a model with their fruits and vegetables. He explains how researching the problem of how to use the fruits and vegetables to make a model of the solar system requires time and patience. The students need to gather a lot of data about each planet before they select the fruits of relative sizes for their solar system model.

> “*Given a three meter sun at one end of the [school] building, the scale model planets we created wouldn't fit in the school. In fact, Pluto would be nearly 15 km away.*”
> —David Whitney

The students access the Internet and accumulate a good deal of information about the planets individually and the solar system as a whole. All the students decide that one critical piece of information is the planets' distances from the sun. Here Mr. Johnston intervenes again, explaining that the distances between the planets and from the planets to the sun are so huge that no classroom model can be truly accurate for distance. He tells the students that one fourth-grade teacher, in an effort to represent the distances accurately, spread out the model planets all over the local community (Whitney, 1995).

***Mr. Johnston's thinking:*** *Mr. Johnston knows that the fruit-and-vegetable model will not be completely accurate, but that is okay, especially if the students come to understand how it resembles the real solar system and how it differs. Later, he will ask them to make comparisons between the model and the real thing.*

To make the calculations more manageable, Mr. Johnston provides the students with distance dimensions in the form of astronomical units. One astronomical unit (AU) equals 93 million miles, the average distance from the sun to the Earth. All the other distances in AUs are relative to that distance. Mr. Johnston distributes calculators to help the students explore the numbers while he uses the SMART Board at the front of the room to write the data (shown in Table 8.1). Together, the students multiply each of the planetary distances expressed in AUs by 93 million miles. The enormity of the numbers indicates to the class how huge the solar system really is.

Now the students turn to the data they have collected on planet diameters, which is given in kilometers (see Table 8.1). Using these data, the students order the planets from smallest to largest. Then they are ready to select the fruits and vegetables that are most representative of the solar system.

For the sun, they choose a huge pumpkin brought in by Mr. Johnston. In reality, the sun's diameter is about 109 times that of Earth, and if the sun were a hollow ball, one million Earths would fit inside. Thus

**TABLE 8.1 The Solar System Data Used by Mr. Johnston's Class**

| Planet | Average Distance from Sun (AUs) | Diameter (km) |
|---|---|---|
| Mercury | 0.4 | 4,878 |
| Venus | 0.7 | 12,104 |
| Earth | 1.0 | 12,756 |
| Mars | 1.5 | 6,796 |
| Jupiter | 5.2 | 142,796 |
| Saturn | 8.5 | 120,300 |
| Uranus | 18.0 | 52,400 |
| Neptune | 30.0 | 48,600 |

the students know that the pumpkin is not really big enough to accurately represent the sun in their model. As for the planets, different groups of students make different decisions. Here are the choices one group makes:

- Mercury: a small cherry tomato
- Venus: an orange
- Earth: an apple, slightly larger than the orange
- Mars: an apricot, approximately half the size of the apple
- Jupiter: a honeydew melon
- Saturn: a cantaloupe
- Uranus: a cabbage
- Neptune: a grapefruit, slightly smaller than the cabbage

For many students, it becomes a challenge to remember which fruit is modeling which planet, so Mr. Johnston instructs each group to make a key.

Once the students have made their selections, it is time to go outside and place the model planets in such a way that they also model the relative distances of the planets from each other and the sun. The class chooses the set of vegetables and fruits just listed as the ones to take outside. Mr. Johnston suggests using 1 meter to represent 1 AU. With this technique, the students observe that the first four planets occupy about 1.5 meters of space, while Neptune is 30 meters away from the pumpkin, the designated sun. The student carrying the grapefruit model of Neptune finds it difficult to see the student carrying the huge pumpkin model of the sun (Figure 8.1).

When the students discuss their model back inside in the classroom, Mr. Johnston asks, "In what ways is our model like the real solar system?" The students offer many responses, including these:

- "All the planets are different, with different textures and insides."
- "The relative sizes of the planets are the same, more or less."
- "We set them up so the relative distances are similar."
- "They're in the order of their distance from the sun."

"In what ways is the model *different* from the real solar system?" Mr. Johnston then asks.

"You can't eat the real planets!" the students point out. And they add other differences as well:

- "The model is so much smaller than the real thing."
- "The planets aren't moving."

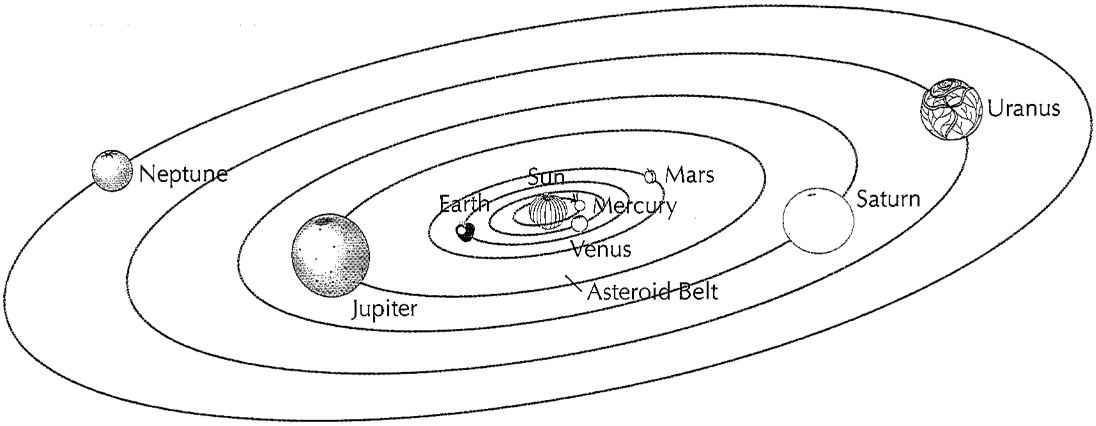


FIGURE 8.1 A model of the solar system using the edible "planets" chosen by Mr. Johnston's class

- "The distances are much, much larger."
- "Some planets have moons."
- "Neptune is blue, not yellow like the grapefruit!"

> ***Mr. Johnston's thinking:*** *The students are doing a good job of evaluating this particular model, and they are beginning to learn a crucial fact about models in general: You should always be aware of how your model differs from the reality it represents. The students are seeking the best solution.*

The remark about planets having moons leads to an interest in adding moons to the model. On another day, the class decides to use miniature marshmallows and toothpicks to represent the moons of the various planets. From their research, the students learn that Mercury and Venus have no moons, but there are more than 155 moons that orbit the rest of the planets in the solar system. Jupiter, with more than 60 moons, has the most. In fact, scientists are still discovering new moons in the solar system. This activity generates further questions. For example, one group wonders if the mini-marshmallow moons are on a similar scale to the planets. They do some research on the Earth's moon and the moons of Jupiter, and they realize that a regular-size marshmallow would be a better model for our moon, which is about one-fifth the size of the apple Earth. They also realize that it would be difficult to include all the planets' moons in their model.

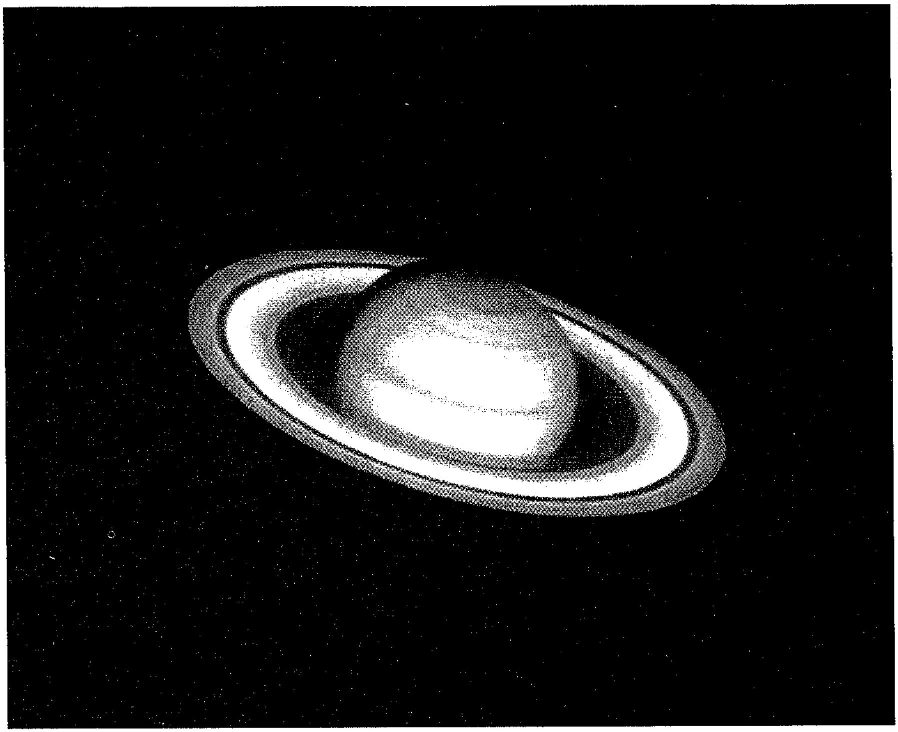
To conclude the lesson, Mr. Johnston asks the students to observe their models closely, think about what they have learned, and write their conclusions in their science notebooks. He asks them to be sure to answer these questions:

- What planets seem similar in size to one another?
- What planets are Earth's neighbors in the solar system?
- What place in the solar system is the Earth in order of distance from the sun? In order of size?
- What is the solar system mostly made up of?

The students finish the session by eating their favorite parts of the model.

## The Teaching Ideas behind This Story

- Inviting the students to generate their own questions about the solar system is a first step toward giving them ownership of the process of gathering the data.
- Typically, solar-system models are constructed out of Styrofoam balls of varying sizes. The assumption people may make when observing this type of model is that all the planets are the same except for their size. That is not true. Planets differ from each other not only in size but also in composition, color, and surface features. For that reason, Mr. Johnston thinks that fruits and vegetables will make a better representation as well as a more interesting one.
- Notice how Mr. Johnston encourages students to discover both the accuracies of their model and its limitations. He also encourages them to learn about Pluto's demotion from a planet to a dwarf planet.
- This experience of gathering data and creating an edible solar system model is directed toward students in fourth grade and higher. You can adapt the activity for students in earlier grades. Instead of numerical data, you can use precut circles to represent the relative sizes of the planets. Students can select their fruits and vegetables using these circles as their data. In the younger grades, each astronomical unit becomes one "giant step."
- It is the teacher's job to select a variety of fruits and vegetables that work as models. Using your data, choose carefully. Obviously fruits are not of uniform size, so your selections will be based on the season and the fruits that are available where you live.
- Notice how Mr. Johnston weaves technology into the lesson without letting it become an end in itself. The use of the WorldWide Telescope helps students visualize the planets and comprehend the



NASA Marshall Space Flight Center (NASA-MSFC)

PHOTO 8.3 An image of Saturn from the WorldWide Telescope. How does this compare with the model shown in Photo 8.2?

vast distances between the planets and the sun. (See Photo 8.3.) But Mr. Johnston also wants the students to gather numerical data and build a more traditional, hands-on model that will lead to detailed comparisons and contrasts. There is a significant difference between using a computer model to explore remote objects and building your own model with the data you collect.

- You can think of model building as a step toward model manipulation, which itself leads to further research, more model building, and deeper understanding. The success of the model is measured by comparing it to their data about each planet.

## The Science Ideas behind This Story

- Our **solar system** is made up of a group of heavenly bodies that move around the sun. The main members of the solar system are the eight **planets**. If you cannot take your students outside as Mr. Johnston did, you can use Table 8.2 to construct a model of planetary distances inside the classroom.
- **Stars** shine by producing their own light.
- The sun is the only member of the solar system that is a star.
- Planets shine by reflecting the light of the sun or of other stars.
- All planets travel in their own **orbits** (closed paths) around the sun, moving counterclockwise around the sun from west to east.
- The Earth is the third planet from the sun in a system that includes the moon, the sun, seven other planets and their moons, and smaller objects, such as asteroids and comets. The sun, an average star, is the central and largest body in the solar system.
- Between Mars and Jupiter is a belt of several thousand **asteroids** of different sizes. These are like tiny chunks of planet, and they also move around the sun.

**TABLE 8.2 Relative Planetary Distances Expressed in Units Suitable for a Classroom Model**

| Planet | Distance from the Point Representing the Sun |
|---|---|
| Mercury | 1.75 inches |
| Venus | 3.25 inches |
| Earth | 4.75 inches |
| Mars | 7.0 inches |
| Jupiter | 2 feet |
| Saturn | 3 feet, 8 inches |
| Uranus | 7 feet, 5 inches |
| Neptune | 11 feet, 8 inches |

- Pluto belongs to another belt of large asteroids called the Kuiper belt. Though these asteroids revolve around the sun as a group, Pluto is not even the largest object in this belt. The definition of a planet requires that it be the dominant gravitational body in its orbit in the solar system. Therefore, in 2006, when an object slightly larger than Pluto was found in the Kuiper belt, astronomers voted to reclassify Pluto as a dwarf planet.
- Scientists continue to seek a larger body than Pluto that can meet the criteria for a new ninth planet!

## Connections to the Next Generation Science Standards

- **NGSS DCIs:**
  - **3–5-ETS1-1: Defining and Delimiting Engineering Problems:** Possible solutions to a problem are limited by available materials and resources (constraints). The success of a designed solution is determined by considering the desired features of a solution (criteria).
  - **3–5-ETS1-2: Developing Possible Solutions:** Research on a problem should be carried out before beginning to design a solution. At whatever stage, communicating with peers about the proposed solutions is an important part of the design process, and shared ideas can lead to improved designs.
  - **5-ESS1-2: Earth and the Solar System:** The orbits of Earth around the sun and of the moon around the Earth, together with the rotation of the Earth on its axis, cause observable patterns. These include day and night; daily changes in the length and direction of shadows; and different positions of the sun, moon, and stars at different times of the day, month, and year.
- **NGSS SEPs:** Students engaged in *developing and using models; analyzing and interpreting data; arguing from evidence;* and *using mathematical and computational thinking.*
- **NGSS CCs:** Students were engaging with identifying *patterns, cause and effect,* and *scale, proportion, and quantity* and systems and system models.

## Exploring Further

To implement this activity in your own classroom, you may want to consider the answers to the following questions:

- What other round objects with diverse colors and textures could model the solar system?
- Suppose you could not find a large pumpkin. What else could you use to model the sun? Why is any object representing the sun in this model—really an inaccuracy?
- What can you learn by planet-hopping with the WorldWide Telescope?
- How does the sun make its own light?
- What are the three basic attributes of a planet?

# 8-3 From Models to Meaning

I have often built an edible solar system with elementary school students, and they tend to remember the project for years afterward. The first time was in my daughter's third-grade class. At her high school graduation, a former third-grade classmate of hers greeted me and said, "I remember when you visited our class and the huge honeydew melon was Jupiter."

The fruits and vegetables make a very useful model for all students, especially for those who need to work with concrete objects to shape comparisons and interpret data. In the same way, using the WorldWide Telescope was a valuable way for students to gather data in order to build their model. But remember that these models were not ends in themselves. Both were steps toward developing a meaningful understanding of the objects in the solar system. In Mr. Johnston's class, the initial activities generated further research, as when one group wondered about the sizes of moons and decided to research the topic.

Making a model and interpreting data based on the model, exploring comparisons between the model and the real object, moving the model as though it were the real thing—these types of activities have important implications for future learning. Besides facilitating the understanding of abstract concepts, the use of models helps to prepare students for the science concepts they will encounter in later grades. For example, balancing chemical equations involves using chemical symbols and a mathematical process to model the actions of real atoms and molecules. As we will see later in this chapter, mental and concrete models of atoms help when thinking about chemical reactions.

In this next science story, Mr. Johnston's fifth graders explore the properties of the planets' orbital paths around the sun. This lesson requires another type of model making.

**solar system**
The sun and the group of heavenly bodies that move around it. The sun is the only member of our solar system that is a star.

**planets**
Principal members of the solar system that move around the sun. In order of their distance from the sun, the planets are Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune. Planets shine by reflecting the light of the sun or other stars.

**star**
A heavenly body that produces its own light. There are billions of stars in the universe, including our sun. About 3,000 stars are visible with the naked eye.

**orbit**
The path of one heavenly body as it travels around another heavenly body.

## SCIENCE STORY

### Making a Model of a Planetary Orbit

On another day, Mr. Johnston distributes string, pencils, centimeter rulers, and pushpins to the class. He asks the students to work with a partner and explains that they are going to draw a shape that represents the path of planets around the sun.

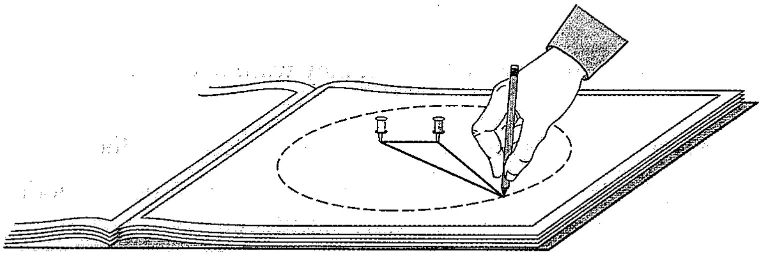


**FIGURE 8.2** Drawing an ellipse (oval) with a pencil, string, and two pushpins

First, he has each pair of students tie a loop with a string about 30 centimeters long. Then he invites them to insert two pushpins toward the middle of one of their science notebook pages, placing them about 8 centimeters apart and making sure the pins go through several pages. The pins should be anchored securely, Mr. Johnston explains. He goes around the room and supervises as each pair of students sets up the pushpins.

Now the students are ready to proceed. They place the loop of string over the pushpins. Then, anchoring a pencil in the loop and keeping the loop taut, they trace a figure that resembles an oval (Figure 8.2). Each team of students compares its shape with those drawn by others. Indeed, the shape is always oval, no matter who draws it.

Mr. Johnston tells them that another word for this oval shape is **ellipse,** and he asks them to label the two points where they inserted their pushpins the **foci** of the ellipse. "In what way is this image different from a circle?" he then asks.

The students say that "you can draw a circle with just one pushpin." Also, they remark, a circle has a center, but the oval does not have one center. Mr. Johnston explains that the planets travel in an elliptical orbit around the sun. We can think of the sun, he says, as being located at one of the foci of the ellipse.

Mr. Johnston has also hung three large, thick pieces of white foam board from hooks at the top of the chalkboard. Each piece is about 1 meter square. He invites students to come up and place pushpins at different points on the foam board. Then he suggests that the students use string loops of varying lengths to determine in what ways the shape of the ellipse changes when the length of the string and the distance between the foci change. (For safety, Mr. Johnston distributes the pins only when the students come up to the board.)

"Be sure to measure the distance between the pins and the length of the string you use in centimeters," he reminds the students. "Record your data in your science notebooks." He watches as the students draw their different ellipses on the foam boards.

***Mr. Johnston's thinking:*** *Mr. Johnston knows that the students' new pencil tracings will change in shape as the length of the string and the distances between the pins increase. The challenge for the students will be to make the leap from these pencil images to the changes in the orbital path of a planet when its distance from the sun increases.*

The students do notice how exaggerated the elliptical shape becomes as they increase the distance between the pins. Mr. Johnston suggests that they keep the distance between the two pushpins constant, changing only the length of the string, and they try the experiment in that way.

"Now, let's imagine that any one of these ellipses represents the orbital path of the Earth around the sun," Mr. Johnston suggests. He labels one of the foci with an *S*, for the sun. "Let's draw a line that represents the distance from the sun to the point on the ellipse where the Earth would be closest to the sun and a line to the point on the ellipse where the Earth would be farthest from the sun." Mr. Johnston draws the lines with a ruler as the students watch.

***Mr. Johnston's thinking:*** *Since the orbital paths of the planets are ellipses, there must always be a point where a planet is closest to the sun and another point when it is farthest from the sun. Mr. Johnston is hoping that the students will see this.*

Next, Mr. Johnston has the students observe pictures and drawings of the solar system from resource books and the Internet. Using these resources as well as their own drawings of the ellipses, the students make inferences about the time it takes for each planet to travel once around the sun. They reason that Neptune's journey must be the longest and Mercury's the shortest.

When the students have completed this stage of their investigation, Mr. Johnston projects a website onto the SMART Board that provides a simulation of the planets in their orbits. Oops! It appears that Pluto is still there. The class notices that. The students reason that it may take some time before newer, more current solar system models replace the older version. The website is still useful, however, because it shows the inner and outer planets as they orbit at their varying distances from the sun. As Mr. Johnston controls the animation, students notice that the Web page also has a chart showing how many Earth years it takes for each of the other planets to revolve around the sun. Mercury makes five revolutions in the time it takes the Earth to make one. This simulation provides the students with another model—a virtual model—of how planets orbit the sun. This virtual model is sometimes called a **simulation**.

## The Teaching Ideas behind This Story

- Notice how Mr. Johnston engages the students in drawing first ellipses of the same size and then ones of all different sizes.
- Mr. Johnston offers labels for their images without precisely defining the terms *ellipse* and *foci*. The students will develop those definitions from their experience of drawing their figures.
- Mr. Johnston uses each opportunity to extend the students' thinking about the solar system. The ellipse drawings become a springboard for further research about the time it takes for planets to complete each revolution around the sun. Mr. Johnston enhances the students' understanding with the simulation website on planetary orbits. This provides an excellent reinforcement of the drawing activity.
- This orbiting-planets simulation also relates to NETS-S standards. The students:
  - "Use models and simulations to explore complex systems and issues."
  - "Collect and analyze data to identify solutions and/or make informed decisions," using "appropriate digital tools" (International Society for Technology in Education, 2007).

## The Science Ideas behind This Story

- A **satellite** is any heavenly body that travels around another heavenly body. The planets are satellites of the sun. The moon is a satellite of the earth.
- The planets' orbits around the sun are elliptical (oval shaped). Most objects in the solar system are in regular and predictable motion. Those motions explain such phenomena as the day, the year, phases of the moon, and eclipses.
- An ellipse has no center. It has two foci or focus points. The sun is located in space at one focus of the planetary ellipses.
- The point in a planet's orbit when it is closest to the sun is called its **perihelion**.
- The point in a planet's orbit when it is farthest from the sun is called its **aphelion**.
- The time needed for a planet to make one complete turn or revolution around the sun is called its year.

## Connections to the Next Generation Science Standards

- **NGSS DCI: 5-ESS1-2: Earth and the Solar System:** The orbits of Earth around the sun and of the moon around the Earth, together with the rotation of the Earth on its axis, cause observable patterns. These include day and night; daily changes in the length and direction of shadows; and different positions of the sun, moon, and stars at different times of the day, month, and year.
- **NGSS SEPs:** Students are engaged in *developing and using models* and *using mathematical and computational thinking*.
- **NGSS CCs:** Students recognized *patterns, cause and effect,* and *scale, proportion, and quantity*.

### Exploring Further

To implement this activity in your own classroom, you may want to consider the answers to the following questions:

- What is the difference between a center and a focus?
- What are some implications of the planets' changing distances as they orbit the sun?
- Do you think planets travel at uniform speed in their orbits? How would you gather evidence for the speed of planets?
- If you were a Martian, how old would you be? That is, what is your age in Mars years?

## 8-4 Shapes of the Moon

In the next science story, sixth-grade students have the opportunity to explore the sky and record their findings. They are seeking patterns, and their results become a model of the moon's orbit around the Earth.

## SCIENCE STORY

### Shapes of the Moon

In the early autumn, the students in a sixth-grade class in rural Maine have been exploring models of the solar system. They have shown an interest in learning how the moon, the Earth's satellite, appears different at different times of the month. One day their teacher, Ms. Hogan, tells them that each of them will begin keeping a *moon-phase journal.* It will give them an opportunity to observe part of the solar system directly, outside the classroom.

In this journal, she explains, they should record their observations of the moon over a period of six weeks. She gives them these general instructions:

- Search the sky on a daily basis.
- Keep daily records of your attempts to see the moon—whether you see it or not.
- When you do see it, include the following things in your journal:
  - a. A description or drawing of what you saw.
  - b. The time and the date.
  - c. What you were doing at the time.
  - d. Anything else you want to write down.
- Become more aware of when the moon is visible in the sky.
- Watch for changes in the moon's apparent shape, and try to figure out the sequence of these changes.

***Ms. Hogan's thinking:*** *Ms. Hogan believes the students can best learn about the moon's phases through direct research, but she wants to leave the precise format of the moon-phase journal open for the students themselves to decide. This open format, she thinks, will be especially useful for students who express themselves better through drawing than they do verbally.*

Over the next six weeks, the students observe the sky and record their data in both words and pictures. Once a week, Ms. Hogan checks their progress and inquires about any difficulties they may be having. At the end of the six weeks, she asks them to bring their journals to class so they can share their observations.

Excited, they arrive in the morning to find large sheets of paper taped to the chalkboards in the room. On each sheet a heading reads, "What We Found Out about the Moon." The students take markers and begin filling in the sheets with their observations, discussing them as they do so.

> ***Ms. Hogan's thinking:*** *There are many ways to encourage the students to share their observations. Ms. Hogan thinks that this method will allow students who are not always comfortable speaking publicly to display their work.*

Here are some of the observations that the students write down for the class to see (reprinted by permission):

- Sometimes, when the moon is rising or setting, it looks yellowish or even orange.
- The moon looks bigger when it is rising or setting than when it is high in the sky.
- You can see the moon in the early morning and the late afternoon at some times of the month.
- You can't see the moon when the sky is very bright in the middle of the day.
- Sometimes you can see a very pale full moon in the sky early in the morning.
- Sometimes, when there is a crescent moon—like a sliver in the sky—you can see the rest of the moon faintly lighted.
- After the crescent moon gets bigger, you can see a half-circle moon in the sky.
- The moon gets bigger as you watch it until it gets to a whole circle—a full moon.
- The moon gets smaller each night after the full moon.
- When the moon is almost full, it is bulging on one side. Then when it starts getting smaller, it is bulging on the other side.
- As the full moon keeps getting smaller, you can see a half-circle moon again in the sky.
- Soon, this half-circle moon looks like a crescent again.
- Sometimes you can only see the moon during the daytime.

## The Same Side of the Moon

In Ms. Hogan's class the moon-phase journals are not the end of the project. One day she brings in a carton of teacups and a box of apples. Each of the teacups has a handle on one side. She asks the students to work in pairs and gives each pair an empty teacup and an apple. She asks the students to imagine that the teacup is a model of the moon and the apple is a model of the Earth. The students turn the cup so that the handle is facing the apple. She instructs them to move the cup in a path around the apple, keeping the handle facing the apple at all times.

The pairs of students do this several times until they see that as the "moon" moves once around the Earth (revolves), it also rotates (turns) once on its own invisible axis. The students then model this process by walking around each other; the students who model the moon keep one elbow pointed toward the students who model the Earth. This activity helps students see that the moon always has the same side facing the Earth because it rotates or spins once during each revolution around the Earth.

## Modeling the Moon Phases

The next step is for the students to create a slightly more elaborate model of the moon's phases as they observed them in the night sky. They use a volleyball to represent the moon, and they darken the room before they start.

Ellen stands in the center of a large space, representing the planet Earth. Patrick, holding the volleyball, walks around Ellen, turning slowly as he goes to keep the same side of the volleyball facing her at all times. Johanna, representing the sun, stands to one side of the moon–Earth system with a strong flashlight, which she shines at the volleyball. As the volleyball reflects the light from the flashlight, these science ideas emerge:

- You can light only half the volleyball (moon) at one time because it is a sphere.
- As it moves around the Earth, only part of that lit half is visible from the Earth.
- The moon rotates once as it revolves once around the Earth.
- The same side of the moon is always facing the Earth.
- Different parts of that side of the moon receive light at different times in its journey.
- The shapes of the moon that we see in the sky are called *phases.*
- When we see the full moon, the entire side of the moon that faces the Earth is reflecting light.

By this time, the moon-phase journal and the following activity have led the students to formulate new questions. They wonder, for instance, about the yellow-orange color of a rising or setting moon; about the "halo" that sometimes appears around the moon; and why the moon appears bigger when it is low in the sky. These are complex issues, and the students explore them in resource books and on the Internet.

## The Teaching Ideas behind This Story

- Giving students more than a month for the project allows them to observe the moon phases repeating themselves. It is another example of sustained inquiry. Besides leading to better understanding of the moon, this process helps the students give meaning to the notion of cycles in other natural processes and in their own lives.
- Although Ms. Hogan hopes the students will understand that the moon's phases repeat and are predictable, she does not give them this information in advance.
- The information the students gain from keeping a moon-phase journal establishes a foundation for the teacup–apple simulation and makes it possible to construct the volleyball model of moon phases. Thus, like Mr. Johnston's edible solar system, the journal is not just an end in itself but also the basis for further explorations. Models of all kinds are important for testing our science ideas.

## The Science Ideas behind This Story

- Like the planets, the moon is visible because it reflects the sun's light. In other words, the light from the sun radiating outward in space in all directions bounces off the surface of the moon.
- The moon appears to have different shapes in the sky as it revolves around the Earth. These different shapes are called **phases of the moon** (Figure 8.3).
- It takes twenty-nine days for the moon to progress from one full moon to the next. This is the time it takes the moon to make one revolution of the Earth, and it is the same as the time it takes the moon to spin (rotate) once on its axis. Because the moon rotates once as it revolves, we see only one side of the moon from Earth.

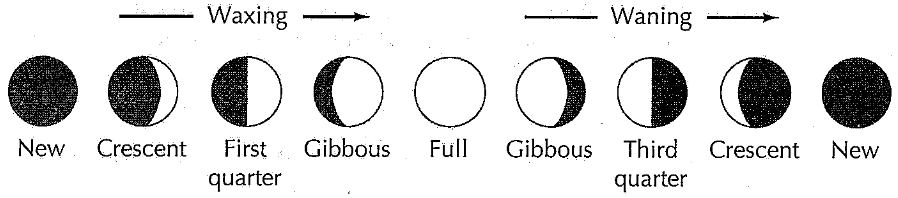


**FIGURE 8.3** The phases of the moon in the northern hemisphere

- As the moon moves around the Earth, different portions of its lighted side are visible on Earth because of the moon's position relative to the sun and the Earth.
- As the moon appears to get bigger in its progress toward a full moon, we say it is *waxing*. As it appears to get smaller after the full moon, we say it is *waning*.

## Connections to the Next Generation Science Standards

- **NGSS DCIs:**
  - **MS-ESS1-1: The Universe and Its Stars:** Patterns of the apparent motion of the sun, the moon and stars in the sky can be observed, predicted, and explained with models.
  - **MS-ESS1-2: The Universe and Its Stars:** Earth and its solar system are part of the Milky Way galaxy, which is one of many galaxies in the universe.
- **NGSS SEPs:** The students were *developing and using models*; *analyzing and interpreting data*; and *obtaining, evaluating, and communicating information*.
- **NGSS CCs:** The students were examining *patterns* and looking at *systems and system models* while examining *scale, proportion, and quantity*.

## Exploring Further

To implement this activity in your own classroom, you may want to consider the answers to the following questions:

- What other types of objects could be used to model moon phases in the classroom?
- What do you think is meant by "earthshine"?
- Have you ever looked at the night sky through strong binoculars or a telescope? What kinds of details do you think you would see that are not observable with the naked eye?
- Imagine keeping a moon-phase journal in South America. What might the images look like?

## 8-4a Using Moon-Phase Journals

Keeping a moon-phase journal has many similarities with keeping a science journal. As we noticed earlier in this book, journaling invites students to observe nature in some way and then reflect on their observations. The moon-phase journal is most appropriate for students in fifth grade or higher, since this exercise requires that they be outside frequently at night. Although on some nights they may be able to see the moon through a window, it is important to alert families to this project and solicit their support and cooperation.

During some parts of the month, the moon may not appear until after the students' bedtimes. Weather can also interfere with viewing. To keep the students from feeling frustrated, it helps to ask them, as Ms. Hogan did, to record all of their experiences, even the unsuccessful ones. And because the moon's period of revolution is about four weeks, it is important to define the project's time period as longer than four weeks; five or six weeks is a good idea so students can observe the repetition of the cycle.

It is my experience that students of all ages, from fifth grade up, take pride in their moon-phase journals. I have even used this project in my teacher education classes, where the preservice teachers become equally enthusiastic about the project. I explain that I hope the experience will enhance their confidence in their abilities to observe. I also make a point of giving them the freedom to

**asteroid**

A tiny chunk of planet-like material that moves around the sun. Between Mars and Jupiter, there is a belt of several thousand asteroids of different sizes.

**ellipse**

An oval shape with no center but with two points of reference called *foci*. Planets travel in elliptical orbits around the sun, which is located at one of the foci of the orbits.

**focus**

One of two points (foci) used to construct an ellipse.

**simulation**

A computer program, virtual construction, or other procedure that imitates a real-world experience.

express and present their observations in any way they choose. "Think of the task as an adventure," I tell my students. "What can you find out about the moon simply by observing it on a regular basis?" Many are astonished to realize that just by looking closely, they can discover a great deal about a natural object that they have seen all of their lives.

When students bring their moon-phase journals to class, I find it useful to have them share the journals with each other before recording their observations. As they review and discuss all the information they have gathered after weeks of keeping a journal, the science ideas really begin to emerge.

If you start a moon journaling project with your students, you'll also find that it offers one other advantage. It will allow you to learn about some of your students' hidden talents. The artists and the poets in particular will have an opportunity to show their creativity.

**satellite**
A natural satellite is any heavenly body that travels around an-other heavenly body. The moon is a satellite of the Earth, and the Earth–moon system is a satellite of the sun.

**perihelion**
The point in a planet's orbit when it is closest to the sun.

**aphelion**
The point in a planet's orbit when it is farthest from the sun.

## 8-5 Making Models with Engineering Design

Now let's examine how an eighth-grade physical science teacher approaches the study of atoms—a subject that lends itself to model building because you cannot see an atom using ordinary optical microscopes. Even using scanning tunneling microscopes, you can map out the images of atoms but not really see them in the visual sense. As you will learn, however, there is a great deal of evidence about what structures make up an atom, and scientists use those data to build models.

As you read the following story, be prepared for the Atom Design Challenge. Design challenges are part of integrating engineering technology into science education. The teacher uses a design challenge to engage the students in designing and constructing their own model of an atom. Notice how much research is needed before design and model building can begin.

**year**
The time needed for a planet to make one complete turn or revolution about the sun.

**phases of the moon**
The various aspects of the moon as seen from Earth, such as the full moon and new moon. These phases reflect changes in the amount of the lighted surface of the moon that we can see from Earth.

## SCIENCE STORY

### Making Models of Atoms

Ms. Murray is an eighth-grade teacher in a middle school in a small suburban community. The students in eighth-grade science explore physical science, addressing topics in chemistry and physics. It is the beginning of the school year, and Ms. Murray is concerned because the topic of atomic structure, which the students will tackle this term, involves very abstract concepts. After researching the best way to introduce concepts related to the structure of the atom, she has decided to explore the history of atomic theory and then let students use their knowledge about atoms to design and construct models of an atom of a particular element.

I am going to be present as a visitor, but before the class begins, I have a chance to ask Ms. Murray what she hopes the students will get out of their unit on atomic structure. She mentions a number of basic concepts about atoms: that an atom is the smallest particle into which an element can be divided and still have all the properties of that element; that an atom is composed of a nucleus and electron clouds; that the atomic nucleus contains protons and neutrons; and so on. But she also hopes, she adds, that "the students will be able to understand the difficulty that scientists had developing the atomic theory, considering that they only had a mental model to work with. I hope they will understand that atomic theory may not be completely correct, and that is why there are always changes to atomic theory over time."

*My thinking: I am impressed that Ms. Murray views atomic theory as a fluid, constantly evolving collection of ideas.*

As the atomic structure unit begins, Ms. Murray distributes newspaper photos and magnifying lenses. She asks students to make observations of the photos using the magnifiers and record their observations in their science notebooks. After a few minutes she says, "What did you notice?" A few students respond that they saw small dots. "Now try to see the dots without the magnifying lenses." Students say they cannot. Ms. Murray then asks if there are other examples of objects that are made up of small parts that can't be seen with the naked eye. Students' answers are varied. Brian says, "Molecules." Nat says, "Pigments," and another student says, "Atoms." Heather adds, "Cells are another example."

Ms. Murray now describes atoms as the building blocks of all matter. She explains that just like cells, which are the building blocks of living things, atoms cannot be seen with the naked eye. She then asks students to record the following question in their notebooks and think about an answer: "How many atoms can fit in a period at the end of a sentence?" Immediately, hands fly up. "What size period, one on the blackboard or one on a sheet of paper?" asks one student. Ms. Murray says that their questions are excellent, and she instructs them to think about a period at the end of a sentence printed in a twelve-point font. She suggests that they take out one of the prior handouts to examine the size of the periods.

After a few minutes, Ms. Murray asks for volunteers to offer their responses. Hands again fly up. The answers, which Ms. Murray writes on the board, range from 1 million to 100 trillion. All the students are eager to know the actual answer, so she informs them that there are roughly 1 trillion atoms in a twelve-point period. Wanting them to see the number, she writes it on the board. One student says, "Wow, a *penny* must have a lot of atoms." Ms. Murray gives the number of atoms in a penny in scientific notation by saying, "Yes, there are two times ten to the twenty-fourth power atoms in a penny." She then writes that number on the board as well: 2,000,000,000,000,000,000,000,000. For homework, Ms. Murray asks the students to come up with their own estimates for the number of atoms in other objects smaller than a penny, using the period and the penny as reference points.

## Exploring the History of Atomic Theory

The next class begins with six trays of materials set up around the room. Each tray contains information about a different scientist, including various books and cards that list addresses of websites. Ms. Murray tells the class, "Since atomic theory has been around for over 2,500 years, it will be good to explore its history." The six scientists are Democritus, John Dalton, J. J. Thomson, Ernest Rutherford, Niels Bohr, and Maria Goeppert Mayer. She asks the students to work in research teams. Each team will use one tray of information to design and construct a poster illustrating the following information:

- The time period in which the scientist lived
- The major discovery the scientist made regarding the atom
- Whether the scientist's theory is still accepted

Using its poster as a teaching tool, each group will teach the rest of the class about that scientist and that portion of history. Students get right to work on their projects, and they continue the next day. Ms. Murray visits each group to check its progress and make suggestions.

*My thinking: It seems that each group of students will become knowledgeable about a specific atomic scientist on their own terms. They will decide what data to include. It will be interesting to see what the work reveals. I am also struck by how Ms. Murray has carefully constructed each group, mixing gender, ability, and ethnicity.*

When the posters are ready, Ms. Murray calls the groups in chronological order, from the earliest scientist to the most recent. As each group presents its scientist, a new piece of the history of atomic theory unfolds. The posters remain on the board in the order of the scientists' discoveries, thus creating a colorful timeline of the history of atomic theory. Halfway through the presentations, one student blurts out, "Oh, I get it, the scientists build on each other." Ms. Murray also has the students describe the big ideas that emerged in each period. The students' comments are summarized in Table 8.3.

**TABLE 8.3 Nuclear Theory Chronology as It Emerged in Ms. Murray's Class**

| Date | Scientist | Experiment or Theory | "Big Idea" of the Time Period |
|---|---|---|---|
| 530 B.C. | Democritus | Material is made of atoms that cannot be split into smaller particles. | All matter is made up of atoms too small to be seen. |
| 1808 | John Dalton | All atoms of any element are the same. Atoms of different elements are different. | Modern atomic theory: every element is made of atoms. |
| 1897 | J. J. Thomson | Cathode-ray experiments reveal existence of negatively charged particles. | Inside the atom are negatively charged particles called electrons. |
| 1911 | Ernest Rutherford | Alpha particle experiments show that atoms have a lot of empty space. | The atom has a positive nucleus, with electrons orbiting around it. |
| 1922 | Niels Bohr | Electrons emit energy only when they change energy levels. | Electrons travel in specific orbital "shells" around the nucleus. Each shell represents a discrete energy level. |
| 1963 | Maria Goeppert Mayer | "Magic numbers" of nuclear particles suggest a shell model of the nucleus. | Particles in the nucleus are also arranged in "shells." Protons and neutrons exist in pairs in the nucleus, and this arrangement gives different atomic nuclei different degrees of stability. |

Ms. Murray then asks the students how many scientists they think actually contributed to the concept of the atom. Several students respond that hundreds did. "Why," says Ms. Murray, "aren't they up on the timeline?" One student answers, "Maybe their discoveries were small, but they made it possible for the big discoveries to be made." Finally, Ms. Murray asks if the atomic theory is 100 percent accurate. The class discusses how the theory has constantly been modified and probably will be modified more in the future. The students are now ready to experiment on their own and create their own mental models.

> ***My thinking:*** *I am struck by how explicit Ms. Murray is making the nature of science and scientific activity. She also illustrates that as one scientist's work was built on by the next, new ideas replaced older ones, and this took an exceedingly long time. Although many people feel it is important to teach these concepts in middle school, teachers do not always see their relevance. Ms. Murray manages to embed these notions in the discussion of atomic structure.*

## Mystery Boxes

The following day, students have a double period of science, and they are asked to perform experiments on "mystery boxes" to determine the contents of each box. Ms. Murray wants the students to develop a mental model of something that cannot be seen but can be known through evidence. This process, she hopes, will model the way in which scientists gather data about atomic particles they cannot see.

Each pair of students receives a sealed box containing various items. They shake the box, listen, and use all their senses to try to determine the number of objects in the box and the identity of each. (The mystery objects include jacks, keys, marbles, small pencils, erasers, dice, and pennies.) Ms. Murray has the students record their procedures, their reasoning, and their answers. After the students present their results to the class, they open the boxes and are surprised at how many objects they inferred correctly. This success builds their confidence in their abilities to use their senses and their reasoning skills. Ms. Murray and the class then relate the mental models they have made of their boxes to the scientific models that evolved, and are still evolving, about the atom.

## Discussing the Nucleus

The following day, Ms. Murray asks the students if they have ever heard the word *nuclear* before. They certainly have. The students mention nuclear fission, nuclear bombs, nuclear power, nuclear warheads, and nuclear power plants. Ms. Murray wonders, "Where do you think the word *nuclear* comes from?" A few students say it comes from the word *nucleus.* One student mentions that a nucleus is in a cell, while others say that it is part of an atom. Together the students review Rutherford's discovery of the nucleus of the atom and some of the other discoveries from their presentations. They talk about the nucleus being within the atom, positively charged, very dense, and made up of particles. The students recall that the nucleus is composed of protons and neutrons, and on the basis of the particles' names, they deduce that protons are positively charged and therefore neutrons must be negatively charged. At this point Ms. Murray helps them to explore other ways of interpreting the word *neutron,* and they realize that they can associate it with the word *neutral.* The students then arrive at the (correct) notion that a neutron has no charge.

They go on to discuss what happens when two like charges are near each other. Using magnets as a reference, they conclude that two likes would repel, so Ms. Murray asks them, "What happens in the nucleus? If protons have like charges, wouldn't they repel each other and break apart the nucleus?" She gives the students time to think about this question and to come up with their own theories. Ms. Murray reassures them that she is not interested in the right or wrong answer but in their thoughts. She tells them, "Scientists always come up with theories that may be incorrect or partially true. It is okay if you are not sure." She lets them know that they can draw pictures to help them visualize their ideas, and she gives them ten minutes to prepare their answers.

When the ten minutes are up, Ms. Murray instructs the students to move their chairs into a large circle. She brings out a small beanbag frog and explains the rules of the discussion: You can talk only if you have the beanie frog, and you can throw the frog only to someone who has his or her hand up. In addition, if you can answer only part of the question, it is okay to pass the frog to someone else.

The students toss the frog around and discuss their theories. Kate says that the attraction between the negative charges of the electrons and the positive charges of the protons causes the nucleus to stay together. Brian says that he too considered this idea, but "then I found a flaw with my theory. If the electrons were attracted to the protons," he says, "they would pull the protons away from the nucleus." Isaac has a totally different theory: that perhaps the neutrons prevent the protons from repelling. He imagines the nucleus as a sandwich: proton–neutron–proton. Jamie says that she can understand how the neutrons play that role because there is no other known reason for their existence in the nucleus.

> ***My thinking:*** *Ms. Murray's use of the frog toss to engage students seated in a circle gives students the responsibility for managing their own participation. This is an effective way to get students talking about their theories.*

Ms. Murray compliments the students on their thinking and then tells them about what scientists call the *strong force,* a force that keeps the nucleus together. This force may derive from the neutrons, but scientists do not yet know exactly how it works. She then invites the students to create their own pictures of what the atom may look like. The students have enough evidence from their historical research to understand that protons and neutrons are in the nucleus and that the electrons move in different ways around the nucleus. When the students have made their drawings, Ms. Murray asks whether there is just one way to draw an atom. The students say no, because no one has ever seen the inside of an atom. She draws a diagram on the board but explains that this is only one way to draw the atom.

## The Periodic Table

The following week, Ms. Murray introduces the class to the periodic table of the elements. She shows how the atomic mass and atomic number are associated with each symbol in the table. After she models the element helium by indicating its two protons and two neutrons in the nucleus of the atom, Ms. Murray asks the students where to put the two electrons. The students all appear to understand that the electrons go outside the nucleus. After discussing the electric charge on the protons and the neutrons, Ms. Murray introduces the theory of electron clouds in the following way.

The class reviews what Bohr said about the way electrons move in orbits, and students discuss whether that theory is still accepted. They think not, because they remember hearing about electron "clouds." Ms. Murray then places a fan in front of the room and tells them to keep their eyes on one of the blades. The challenge is to follow that blade when the fan begins to move.

Ms. Murray turns the fan on the low setting, and within a few seconds a voice calls out, "I lost it." I am assisting with the fan, so I ask students if they know roughly where their one blade is. "In that circle," Shana says. Ms. Murray asks, "Does anyone know *exactly* where the blade is?" The class answers, "NO!" She explains, "Just like you kind of know where the blade is, but not exactly, scientists kind of know where electrons are, but not exactly. That is why scientists talk about *electron clouds.*" On the board diagram she draws a broad space around the electrons and shades it in. "Scientists think that electrons are somewhere in this area, but they don't know exactly where."

Ms. Murray then asks the students if they have peeled an onion before. Hands shoot up. She takes out an onion and asks whether it will be hard or easy to remove the top layer. "Easy," the class agrees, so she removes it. When she asks about the next layer, the students are a little unsure. She removes that layer, and a few students say the task was a little harder. When she goes on to ask about the third layer, the students say it will be harder to remove, and indeed it is.

Now Ms. Murray makes an analogy between the onion layers and electrons in the atom. The class spends a good deal of time discussing electron shells and electron clouds and trying to make sense of tiny particles moving very quickly at different distances from the nucleus of the atom. The onion proves a helpful tool. In the following days, the class examines the periodic table and the numbers in each of the table's boxes. Students then make a model of the table using fruits and vegetables. Their understanding of the atoms of each element is really beginning to grow.

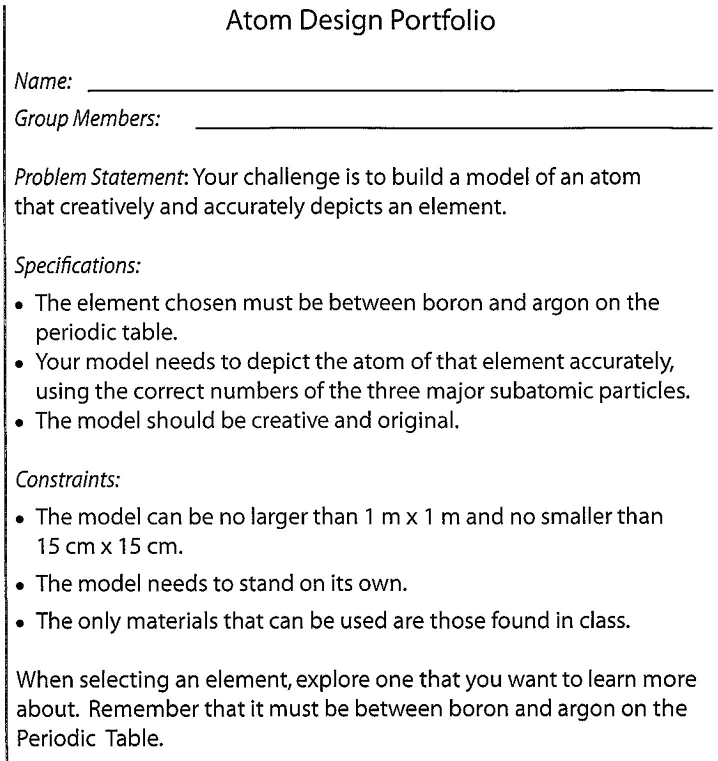
## The Atom Design Challenge

In week three, Ms. Murray poses a design challenge. She hands each student a booklet titled "Atom Design Portfolio." On the booklet's face is a page that states the challenge, as shown in Figure 8.4. In groups, students are supposed to build their own models to depict the atom of a particular element. The booklet contains various sections to guide students through the process: Selecting Your Element, Research, Resources, Brainstorming, Sketches of Possible Solutions, Selecting the Best Solution, Reflecting on the Process, and Evaluation. Ms. Murray explains each of the specifications listed in Figure 8.4 and addresses the importance of being creative and original. The students are excited and full of questions. Ms. Murray explains the materials she will bring (including balloons, markers, clay, rubber bands, and Popsicle sticks), and students generate a list of common materials they can bring from home (bubble wrap, string, felt, milk cartons, egg cartons, Styrofoam, and so on).

To begin the project, Ms. Murray has each student individually choose two possible elements to explore and list a reason why each would be interesting. Then the students meet as groups to discuss their choices, agree on a single element to use for the project, and begin to discuss the most important questions. The next class period is spent in the library, where the students use books and the Internet to research answers to their questions about their element.

The following day, the students begin to brainstorm their designs for their atoms, incorporating a lot of the data from their research. For instance, the group designing an atom of sulfur wants to use yellow materials. After the day of brainstorming, Ms. Murray and the students together develop a *rubric* for evaluating their final solutions (Table 8.4). (You will read more about rubrics in Chapter 13.) Many of the students want to know what they need to accomplish to receive a perfect score; they are not interested in receiving anything less.

Each group is required to draw three possible models for their design project, choose one, and then have the final sketch approved by Ms. Murray. She wants to make sure that when construction begins, the students will know where to start. Some groups come to agreement more readily than others. Ms. Murray



Atom Design Portfolio

*Name:* ____________________

*Group Members:* ____________________

*Problem Statement*: Your challenge is to build a model of an atom that creatively and accurately depicts an element.

*Specifications:*

- The element chosen must be between boron and argon on the periodic table.
- Your model needs to depict the atom of that element accurately, using the correct numbers of the three major subatomic particles.
- The model should be creative and original.

*Constraints:*

- The model can be no larger than 1 m x 1 m and no smaller than 15 cm x 15 cm.
- The model needs to stand on its own.
- The only materials that can be used are those found in class.

When selecting an element, explore one that you want to learn more about. Remember that it must be between boron and argon on the Periodic Table.

FIGURE 8.4 Cover sheet for the Atom Design Challenge

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actively participates in two of the groups that struggle to find consensus. Four of the groups need hardly any assistance from her at all.

> ***My thinking:*** *When I ask one group why they have chosen the element boron, they all say, "Because we didn't know anything about it." I am impressed by this group's willingness to take ownership of their learning.*

Over four class periods, the students complete and decorate their models. Every day, the students come into class excited; the sense of pride they take in their work can be seen in their eyes and heard in their voices. A student in one of the groups says, "Ms. Murray, look at our project! Doesn't it look great?"

> ***Ms. Murray's thinking:*** *Ms. Murray now believes she has accomplished something bigger than teaching the students about atoms. Her students no longer need her to tell them their work is great. They have gained confidence in it, in each other, and in their knowledge. She is very proud of them.*

When the students present their final design projects, they demonstrate their understanding of atomic structure as well as the specific uses of their elements. Overall, the class has built models of boron, carbon, aluminum, magnesium, phosphorus, and neon, and the models are quite different from one another. The neon group has used Popsicle sticks, beads, tape, paper towel rolls, and other materials to create a model of neon's ten protons, ten electrons, and ten neutrons. When they present this model, the students explain that neon is a colorless, odorless gas that is lighter than air and is used in neon lights. The students point out the two energy levels for neon's electrons and show how they twisted pipe cleaners around the sticks to represent electron clouds.

The boron group has used a white triangular Styrofoam base to hold a nucleus with five protons and six neutrons. Around the nucleus, fanlike blades represent boron's five electrons in two energy levels (Photo 8.4). The students are especially proud of these electron clouds. They talk about the scientists who discovered boron and share the fact that boron is used in pyrotechnics and flares to produce a green color. It has also been used in some rockets as an ignition source.

TABLE 8.4 Rubric for Design Project

| Category | Score | Description |
|---|---|---|
| **Success of the solution** | 4 | The solution solves the problem statement. Detail and design are excellent. Hard work and planning are obvious. |
| | 3 | The solution solves the problem statement, and the constraints and criteria are met. |
| | 2 | The solution solves the problem, but not all constraints and criteria are met. |
| | 1 | The solution does not solve the problem; constraints and criteria are not met. |
| **Creativity of the design** | 4 | The solution is unique; never or seldom has this design been formulated. |
| | 3 | The solution is functional but not unique. |
| | 2 | The solution is similar to a number of others; it may be a modification or interpretation of another group's solution. |
| | 1 | The solution has been copied from another group's. |
| **Accurate measurement and calculation** | 4 | Rulers were used appropriately to measure material throughout the process of planning and implementing ideas. |
| | 3 | Rulers were used appropriately during the implementation of ideas. |
| | 2 | Measuring devices were rarely used. Some mathematical calculations are incorrect. |
| | 1 | Errors in measurement are evident. |

***My thinking:*** *I find it wonderful that the electric fan lesson carried over to this group's stunning model of electron clouds.*

## The Teaching Ideas behind This Story

- By examining historical scientific models, Ms. Murray gives the students insights into the nature of science and the role of historical, philosophical, and technological contexts in the development of scientific knowledge.
- Ms. Murray discards the rigid view of what an atom looks like in favor of a more open-ended (and more scientifically accurate) approach. By doing this, she allows her students to develop a much deeper knowledge of atomic structure than if they had merely studied the usual pictures and built conventional models.
- To make abstract concepts concrete, Ms. Murray uses her own everyday models—the electric fan and the onion.

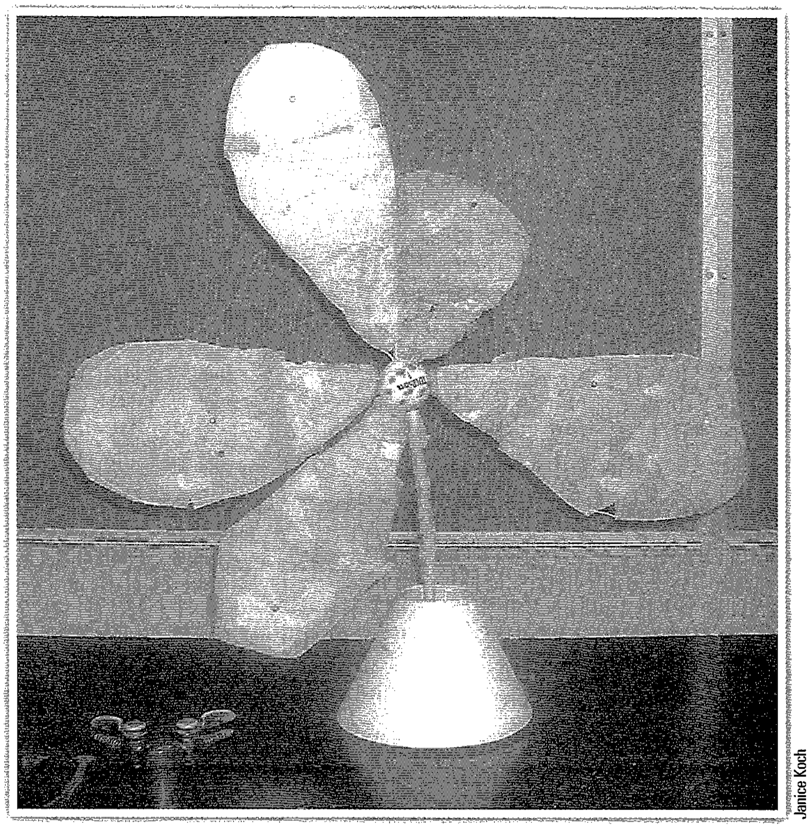

PHOTO 8.4 The model of a boron atom made by students in Ms. Murray's class.

- In a **design challenge**, students plan, research, design, and construct solutions that lead to a product or a process. Essentially, design is the technological counterpart of the science-as-practice process. Today we understand that all students should develop abilities of technological or engineering design. Students' work with scientific investigations can be complemented by activities in which the purpose is to meet a human need, solve a human problem, or develop a product. Students should make and compare different proposals in the light of the criteria they have selected. "They must consider constraints—such as cost, time, tradeoffs, and materials needed—and communicate ideas with drawings and simple models" (National Research Council, 1996).

## The Science Ideas behind This Story

- As you saw in this chapter, models are important in scientific research, both in formulating hypotheses to be tested and in describing scientific phenomena.
- Science has revealed a great deal about the structure of the atom. Scientists are now conducting experiments to explore the structure of the nucleus and the forces that hold it together.
- Atoms are so small that we cannot see them with an ordinary microscope. In the past three decades, however, new types of microscopes, such as the atomic force microscope, have allowed us to see atoms and investigate their properties.
- Atoms of different elements have different properties and differ in size.
- All atoms are electrical in nature. They have positively charged particles called **protons** in their nuclei and have negatively charged particles called **electrons** surrounding the atomic nucleus. The number of protons in a given atom is equal to the number of electrons; hence, atoms are electrically neutral.

- In addition to protons, the atomic nucleus contains **neutrons**, particles without an electrical charge.
- The mass of a proton is equal to the mass of a neutron. Electrons have only about 1/1,800 of the mass of a proton or neutron.
- Electrons revolve around the nucleus in distinct energy levels or "shells." Rather than call these paths *orbits*, scientists today prefer the term *orbital*, which refers to the wavelike function of the electron. Electrons exist both as particles and as waves. The various orbitals are at different distances from the nucleus of the atom.
- Because we can never know the exact position of an electron in its orbital, it is useful to think of these particles as moving in **electron clouds**, general areas where they may be found. The densest part of the cloud is the area where the electron is most likely to be.
- Each electron cloud or energy level has a maximum number of electrons that it can hold. The first major energy level has a maximum of two electrons; the second, a maximum of eight electrons; and the third, a maximum of eighteen electrons.
- The farther away the electron is from the atomic nucleus, the more readily it can leave the atom.

## Connections to the Next Generation Science Standards

- NGSS DCIs:
  - **MS-ETS1-1: Defining and Delimiting Engineering Problems:** The more precisely a design task's criteria and constraints can be defined, the more likely it is that the designed solution will be successful.
  - **MS-ETS1-2 and MS-ETS1-3: Developing Possible Solutions:** There are systematic processes for evaluating solutions with respect to how well they meet the criteria and constraints of a problem.
  - **MS-ETS1-4: Developing Possible Solutions:** A solution needs to be tested, and then modified on the basis of the test results, in order to improve it.
  - **MS-PS1-1: Structure and Properties of Matter:** Substances are made from different types of atoms, which combine with one another in various ways. Atoms form molecules that range in size from 2 to thousands of atoms.
  - **MS-PS1-2 and MS-PS1-3: Structure and Properties of Matter:** Each pure substance has characteristic physical and chemical properties that can be used to identify it (for any bulk quantity under given conditions).
- **NGSS SEPs:** Students were *asking questions and defining problems, developing and using models, analyzing and interpreting data, using mathematical and computational thinking*, and *constructing explanations and designing solutions.*
- **NGSS CCs:** Students were examining *structure and function, patterns*, and *cause and effect.*

## Exploring Further

To implement this activity in your own classroom, you may want to consider the answers to the following questions:

- How does Ms. Murray's atomic structure unit differ from conventional ways of teaching atomic theory?
- How do the groups of students in Ms. Murray's class demonstrate what we know about how students learn?
- What other middle school science topic lends itself to a design challenge?
- Which parts of this science unit might be adapted for collaborative teaching with a history teacher? With an English teacher?

## Nanoscale Science and the Study of Atoms

You have probably heard about *nanotechnology*, the design and production of structures, devices, and systems on the scale of an atom or molecule. The term is derived from *nanometer*, meaning one-billionth of a meter. This technology is behind advances in products ranging from computer processors to sunscreens to tennis balls, and there is tremendous potential for nanoscale robotics—for instance, little machines that might swim through your blood vessels to attack disease. Not surprisingly, educators have begun developing science units that explore nanotechnology. **Nanoscale science** refers to inquiry-based activities designed to help middle and high school students explore the unique properties and behaviors of materials at the nanoscale (Jones et al., 2007).

In exploring the nanoscale with their students, teachers face the same problem that Ms. Murray did: how to guide students in forming a mental model of something so small they can't see it. In one exercise developed by nanoscience teachers (Jones et al., 2007), the teacher writes the number one thousand on the board (1,000) and asks students how much larger one billion is. This question produces many different responses. The answer is actually one million: A billion is a million times larger than a thousand. Then students are asked how big a container would need to be to hold one billion golf balls. When students investigate this question, they learn the golf ball is one billionth the size of approximately 400 classrooms (assuming each classroom is 10 meters by 10 meters by 3 meters). Holding a billionth of these classrooms' volume in their hand introduces the students to the incredible scale of nanotechnology, a billionth of a meter! If you filled the average bathtub with table salt, there would be approximately a billion grains of salt. One grain of salt in that tub is a billionth.

As older students study the structure of the atom, they will be exposed to nanoscale science and to a new frontier in which scientists can manipulate materials on the atomic scale and produce new structures that could serve society in many different ways. Here are some resources for lessons and activities related to nanoscale science:

- Jones, M. G., Falvo, M. R., Taylor, A. R., & Broadwell, B. P. (2007). *Nanoscale Science: Activities for Grades 6–12*. Arlington, VA: NSTA Press. Twenty investigations help students explore the properties and behavior of materials at the nanoscale.
- *Nanoscale Science*. This site from the National Nanotechnology Infrastructure Network is a guide to understanding the tools used in nanotechnology and exploring the images that these tools can produce. There are lessons and activities that may be appropriate for high school and advanced classes in middle school. http://www.nnin.org/education-training/k-12-teachers/
- *NanoScale Science Education*. This website includes links to activities for elementary and middle school grades. http://www.ncsu.edu/project/scienceEd/

## 8-6 Engineering Design Technology

The design challenge that Ms. Murray posed for her students leads us to the subject often known as **design technology** or *engineering design*. It requires students to identify and state a problem, design a solution, implement a solution, and evaluate the solution.

**design challenge**
In design technology, a specific problem that students are asked to solve by designing and constructing a product or an optimal solution.

**proton**
A positively charged particle in the nucleus of an atom.

Think of it this way: As part of science as practice, students engage in the exploration and analysis of natural phenomena. They manipulate materials, plan experiments, make observations and inferences, and try to find answers to problems that they pose. As part of design technology, students plan, research, design, and construct solutions that lead to a product or a process. Like science practices, engineering practices are recursive and iterative processes—trying one solution and, on the way to it, finding another.

When we add engineering practices to science practices, we ask students to solve a problem—often called a design challenge—that requires them to use some of the scientific and/or mathematical ideas they are exploring through their scientific investigations. The solution typically involves constructing a product or process that meets stated specifications or *criteria* and that is built according to specific *constraints*.

## 8-6a Design Portfolios

As you saw in Ms. Murray's class, design projects often use a portfolio as a tool to assist students in the design process. Design portfolios include the problem statement, specifications or criteria and constraints, and several other sections.

From the sound of the term *engineering design*, you may think it applies mostly to students in middle grades and high school. But the abilities of technological design are developed at all grade levels. What might a design challenge for younger students look like? How do they define problems and seek solutions?

Think back to the story of liquids and density in Chapter 7. The liquid "toys" that the fifth graders constructed are another example of design technology. Design challenges are one more way to apply the core concepts in science to another context.

In the next chapter, fourth graders are studying electrical circuits. Students in third or fourth grade often read the classic children's book *Stuart Little* by E. B. White (1945), a story about a family whose younger son appears to be a mouse. Imagine a design challenge in which the students are asked to design and construct a four-room home for this beloved mouse, and the criteria require a light for each of the rooms. Stuart the mouse stands two inches tall, so mathematical measurements involving scale are required to construct the house. Knowledge of how to wire the ceiling lights and install a switch helps students apply their understanding of electrical circuits. The students would then evaluate their solutions and most likely would learn a great deal about series and parallel circuits as well as about larger themes of proportion and scale. As you will see, Ms. Travis's class in the next chapter begins to see the applications of their understanding of electrical circuits to their construction of lighted "shoebox" rooms.

**electron**
A negatively charged particle found in the atoms of all elements. Electrons revolve around the nucleus of the atom in different orbitals or "shells"; each shell represents a distinct energy level. Each electron is thought to be a particle of negative electricity.

**neutron**
A particle with no electrical charge found in the nucleus of an atom.

**electron cloud**
A term for the general area occupied by each "shell" or energy level where electrons orbit the nucleus of an atom. The metaphor of a "cloud" emphasizes the fact that we cannot know exactly where an electron is at a particular time; we just know that it is somewhere within that general area.

**nanoscale science**
Inquiry-based activities designed to help middle and high school students explore the unique properties and behaviors of materials on the scale of an atom or a molecule.

**design technology (engineering design)**
The technological counterpart to the science-as-inquiry process. For students, the design process typically involves solving a problem by constructing a product that meets a set of established criteria, called specifications.