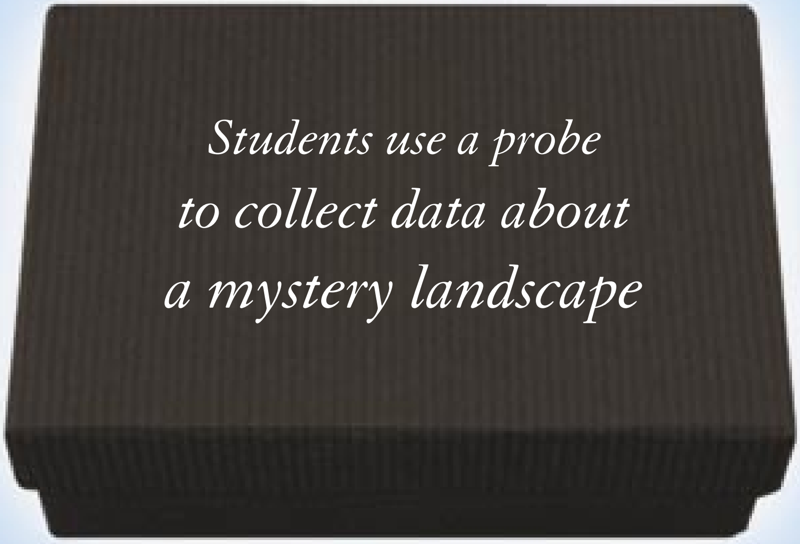
Inside the Black Box



Students use a probe to collect data about a mystery landscape

Yvonne S. Kao, Anthony Cina, and J. Aura Gimm

Scientists often have to observe and study surfaces that are impossible or impractical to see directly, such as the ocean floor or the atomic surfaces of objects. Early in the history of oceanography scientists dropped weighted cables to the bottom of the ocean. By moving across the ocean at regular intervals and keeping track of how deep the cables went, the scientists produced a rough map of the ocean floor. Nowadays, scientists can calculate how deep the ocean is at any point by sending sound waves from a ship to the ocean floor and keeping track of how long it takes for the sound waves to return to the ship.

The black box activity described in this article, created as part of the National Science Foundation–funded Internships in Public Science Education Program (IPSE) at the University of Wisconsin–Madison, introduces students to the idea of remote imaging and scanning probe microscopy (SPM). The activity can be incorporated into chemistry or other physical science classes to meet content standards on the structure and properties of matter, and technological design (NRC 1996, pp. 178 and 192).

Students use a probe to collect data about a mystery landscape inside a “black box” and then use the data to build a marshmallow model of the contents of the box.

This article is based on materials available on the "Exploring the Nanoworld" website (*http://mrsec.wisc.edu/edetc/modules*) under the heading "How can we see what we cannot see?" The activity was initially developed as part of the authors' Research Experience for Teachers (RET) program.

SPM background

SPM refers to a class of microscopes that use a probe to collect data about a sample's surface, much the same way that oceanographers have been able to collect data about the ocean floor. SPM was developed in the 1980s by Swiss scientists Gerd Binnig and Heinrich Rohrer—who were awarded the Nobel Prize in Physics in 1986 for their work—and is powerful enough to image individual atoms. [**Editor's note:** For an activity that allows students to construct a model SPM, refer to "Seeing the Unseen" on p. 58 in this issue.]

Scanning tunneling microscopy (STM) is a form of SPM that uses a probe that ends in a single-atom point. STM is used to image the surface of metals. The probe is typically made of tungsten or platinum and is positioned a few nanometers above the surface of the sample. Applying a small voltage to the gap between the probe and the sample causes a small current of electrons to flow through the gap. The strength of the current depends on the electron density at the probe tip—the electron cloud is denser near an atom's nucleus—and the amount of voltage applied to the tip. As the probe moves back and forth, a computer records the changes in voltage required to keep the electron flow constant. This data is used to assemble the final image (Bedrossian 2006).

Atomic force microscopy (AFM), another form of SPM, can be used to image both metals and nonmetals. In AFM, the probe is again shaped like an extremely sharp needle that ends in few atoms. This probe is dragged across a material's surface and the tiny mechanical forces between the probe and the material are detected. These forces cause a cantilever to move up and down. These movements can be more closely monitored by reflecting a laser beam off the top of the cantilever into a photodetector that measures the displacements. The data is then transformed to create an image of what the material's surface looks like at the atomic level. Students' exploration of remote imaging with the black box (Figure 1) more closely resembles AFM than STM.

FIGURE 1

Making the black box.

Activity materials

- One black box per group of 2–3 students
- Thin sticks, such as barbecue skewers or straws
- Rulers (optional)
- Copies of grid or graph paper (2 sheets per 2–3 students)
- Markers or colored pencils (optional)
- Miniature marshmallows (be sure to take the marshmallows out of the bag and spread them out on waxed paper to allow them to dry for a day or two before the activity so they are harder and easier to use) or other small, uniform, cubic items to use as building blocks (e.g., such as Lego blocks of the same dimension)
- Glue

Construction

Teachers should gather one shoebox for each small group of 2–3 students. Each box should have a mystery landscape glued to the bottom. This landscape can be made with household objects like rolls of tape, plastic party cups, containers in various sizes, and molded figures of clay or plaster. We have manufactured landscapes out of oddly shaped scraps of wood as well as hard foam shapes typically used for floral arranging. If teachers decide to use floral foam, they should seal the landscape with a layer of glue so that students cannot poke through it easily. The important thing is for the landscape to have a highly varied topography. Also, students seem to be more engaged if the contents of each box are different. Small, excited crowds often gather for the revelation of what is really in each box.

Be sure to tape the boxes shut so that students cannot see what is inside. Punch holes in the lid of each box in a grid pattern, spaced approximately 2 cm apart. The boxes should be reusable year after year if they are handled properly. If teachers have the time and materials, each group of students can be asked to create their own black box and challenge another group to map it.

FIGURE 2

Landscape inside a black box (left) and corresponding marshmallow model (right).

[Note: Marshmallows are used not as absolute scale but rather relative scale and they are larger in unit scale than the measuring stick used.]

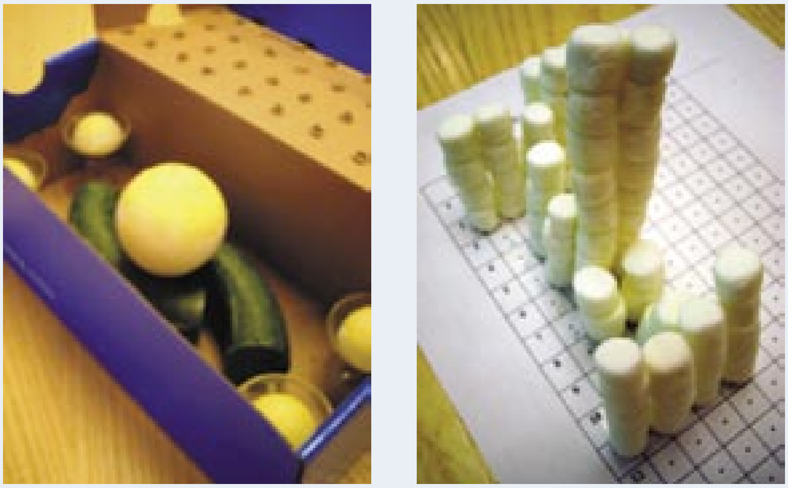
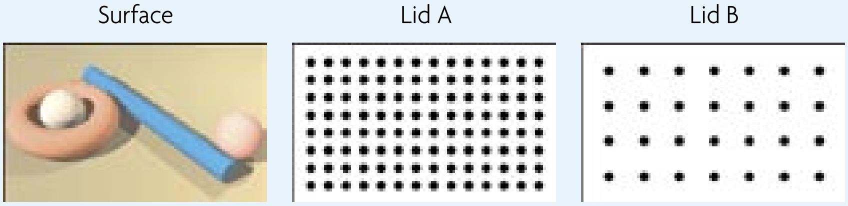


FIGURE 3

Example exam questions.

Question 1:

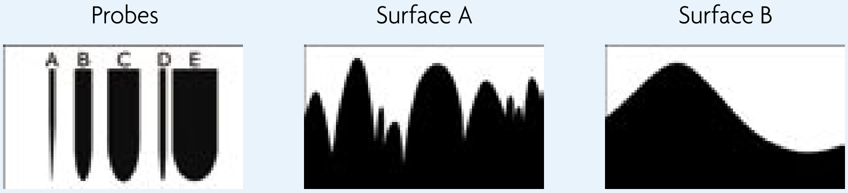

Surface

Lid A

Lid B

A class of students is doing the black box activity. Two groups, A and B, have boxes with the surface on the left inside it. The only difference is that there are many more holes punched in the lid of Group A's box (Lid A) than in the lid of Group B's box (Lid B). Will Group A's finished model look like Group B's model? What will look different or the same? If you think there will be differences, what will cause these differences?

Question 2:



Probes

Surface A

Surface B

a) You are a scientist who maps surfaces. You have probes A, B, C, D, and E, shown on the left. Rank the probes from the one that will give you the least detail to the one that will give you the most. Explain your answer.

b) Which probe would give you the best results for mapping Surface A? Why?

c) Which probe would give you the best results for mapping Surface B? Why?

d) If you wanted to map a surface in so much detail that you could see the individual atoms that make up the surface, what size would your probe have to be?

Mapping the black box

Before beginning the activity, teachers should ask students if they can think of ways we "see" things without directly observing them. For example, "How do bats find insects in the dark? How do blind people read? How do we know what the bottom of the ocean looks like? Or the surfaces of other planets?" Students may have heard of some ways that people can "see without seeing," such as by using radar, sonar, or other types of imaging. Teachers should briefly explain how some of these technologies work. For more information on different ways of seeing without seeing, we recommend the following articles online at *HowStuffWorks*: "How Bats Work: Seeing with Sound" (Harris 2006) and "How Ultrasound Works: What is Ultrasound?" (Freudenrich 2006).

Each pair or group of three students should have a black box, a measuring stick, a ruler (if centimeters are not marked off on the measuring stick), and a grid (Figure 1). Students should measure the depth from the top of the box to the landscape by pushing the stick through each hole until they feel the stick just touch the surface of whatever is inside. Then students should hold or mark the point on the stick where it meets the lid of the box, remove the stick, and record the distance from the end of the stick to this point on their grid. Students may round to the nearest centimeter. Teachers can speed this process up by marking off centimeters on the sticks before beginning the activity. When students are finished, each group should have a grid of measurements, with each measurement corresponding to a hole in the box.

Students will need to transform the data before they can build models. Right now students have a grid of depths; what they need to build their model is a grid of heights. To transform the data, students should measure the height of the box and then subtract each of the depths from this number and record the resulting height measurement on a new grid. At this point, students can color-code the grid so that each height is a different color. This creates a two-dimensional topographical map of the landscape that can be used to determine the major landforms.

Students can now use their two-dimensional map to build a three-dimensional model out of miniature marshmallows. This works best if the marshmallows have been allowed to dry and become harder and less sticky. Since each mini-marshmallow is about 1 cm^3 on each side, students can construct a simple model of the landscape by stacking and gluing the appropriate number of marshmallows for each point in the grid. In order to avoid disturbing completed parts of the model, students should start building in one corner and grow the model from that corner. When they have finished their models, students can open the black box and compare their model to the original landscape (Figure 2, p. 47). Although this adds interest, students should be reminded that scientists usually cannot "open the box" and directly see what is inside.

At the end of the activity, teachers should explain to students that while they used a stick to probe the surface and recorded data by hand, scientists may use sound waves, radio waves, or other probes to study surfaces of all sizes and record data using computers. (As indicated earlier in this section, some of these technologies can be discussed before beginning the activity.) Teachers then ask students to think about the limitations of collecting data in this fashion. If, for example, the landscape included a bridge structure or an outcropping, would the probe detect the space underneath? Teachers should ask students to suggest ways for improving the mapping technique to capture more detail. Suggestions may include punching more holes in the top of the box to get data from more points on the surface, using a smaller unit of measurement (e.g., millimeters instead of centimeters), or punching holes in the side of the box in order to get data from a different dimension.

Assessment

Teachers should make sure students understand that the scale of the probe is directly related to how much detail we can see. In this activity, the scale (resolution) of the probe is represented by the distance between the holes punched in the lid. If the distance between the holes were zero, students would be able to freely drag the probe across the surface and collect data from an infinite number of points. Students should also understand that there is a tradeoff between the level of detail and time—the finer the probe (the more holes in the box and the greater resolution, or the capability to distinguish between separate features), the more time it will take to map the surface. This tradeoff means that scientists need to choose an appropriate probe based on what they hope to see.

One way to assess students' learning on this activity is to create different combinations of surfaces and probes and ask students to predict what would happen if they tried to map the surfaces with the probes. This could be given as a lab-practical-style exam, with the combinations of surfaces and probes set up at different stations around the classroom for students to refer to as they answer questions, or as a paper-and-pencil test using pictures of the surfaces and probes. Two example exam questions are given in Figure 3.

Question 1 (Figure 3) assesses if students have learned the relationship between probe size and level of detail within the confines of the task. Since the two groups are mapping the same surface, the basic structure of the two models should be similar. However, Group A's model will be much more detailed than Group B's. Students may also indicate that Group A's model will be a more detailed and better model since there are more data points.

Question 2 (Figure 3) assesses if students are able to generalize what they learned during the black box activity. The thickest probe, E, will give the least detail; C, B, D, then A will give the most detail. The thinner probes are able to get into the nooks and crannies that the thicker probes cannot. Probe A would probably be best for mapping surface A, since it contains a lot of narrow valleys. For surface B, the size of the probe does not really matter since there is so little detail to see. Probe E would allow the surface to be mapped the most quickly. In order to see individual atoms on a surface, the tip of the probe would also have to be on the atomic scale.

SPM allows us to see structures as small as individual atoms because the probes used have tips that are only one atom wide. The development of SPM has led to great strides in nanotechnology—a field dedicated to the study of structures and the manipulation of properties on the scale of atoms and molecules. Now that scientists can see individual atoms, they can try to pick them up and manipulate the atoms, even using these building blocks of matter to build new structures and technologies. For more information on what kinds of nanotechnology might be possible, see "How Nanotechnology Will Work" (Bonsor 2006) from *HowStuffWorks*. Public knowledge of nanotechnology currently remains largely confined to science fiction and pop culture, but nanotechnology has the potential to change our lives in the future. ■

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