Mapping the Unknown
Atomic Force Microscopy and Other Scanning Probe Microscopy Techniques

What it Atomic Force Microscopy and Scanning Probe Microscopy?

Scanning Probe Microscopy is a general name for a set of techniques used to image atomic surfaces. With the help of Scanning Probe Microscopy technologies, scientists have been able to create images or "pictures" of atomic surfaces. With these technologies, we are able to "see" what atoms look like. There are a number of techniques. All of them employ some sort of probe that is run across the surface of a material to gather data. These probes usually measure some kind electrical and magnetic forces between the probe and atomic surface. This data is then used to create images of the surface. More in-depth information is contained in the Teacher Background section below.

Unit Overview

Imaging unknown surfaces is an important part of scientific research. It is often impossible or impractical to observe some surfaces directly. Surfaces of other planets, the ocean floor, and the atomic surfaces of objects must be observed and mapped indirectly. Accurate data gathering and the use of computers to put the data into a visual image are explored in this activity. In this activity, students gather data about an unknown surface inside a shoebox, record the data, and transform the data into 2D and 3D models of the unknown surface. If Microsoft Excel is available, students may also enter the data into a spreadsheet and create a 3D image.

Remote imaging has long been used in the study of the ocean floor. Early in the history of oceanography, scientists would drop very long cables with weights attached to the end of the cable to the bottom of the ocean. By moving across the ocean at regular intervals and by keeping track of the depth cables went, a rough map of the ocean could be made. With improved technology, scientists used sound waves sent from a ship to the ocean floor. By keeping track of how long it took for sound waves to return to the ship, they could calculate how deep the ocean was at that point. In very similar ways, satellites are able to send out waves (often radar waves) to an unknown surface and keep track how long it takes for these waves to return to the satellite. Again, the time it takes for the waves to return to the satellite can be used to calculate how far way the surface is from the satellite.

This investigation focuses primarily on Atomic Force Microscopy. Atomic Force Microscopy (AFM) uses a probe that ends in single-atom point. This probe is essentially dragged across the surface of a material. As this probe is dragged across the material's surface, the mechanical force between the probe and the material is measured. This data is used to create images of the atomic surface. In *Mapping the Unknown*, students figure out what is inside a mystery box using a simple probe, record the data,

and create two-dimensional and three-dimensional images of the unknown surface inside the box. This process is highly analogous to the process of Atomic Force Microscopy.

Purpose

This unit is designed to introduce students to the idea of remote sensing and mapping, to help students understand ways scientists can create maps of unknown surfaces without seeing those surfaces, to show students how numerical data can be transformed into surfaces using 3D graphing, to help students understand the role of probes and computers in creating 3D images of unknown surfaces, and to familiarize students with Atomic Force Microscopy and Scanning Probe Microscopy.

Teacher Background on Scanning Probe Microscopy

The following material contains background information for the teacher about Scanning Probe Microscopy. It is far too detailed to be used with middle school students. It is provided as a way of helping teachers become more familiar with these techniques. Another excellent source of information about this topic is a very readable article about this topic at HowStuffWorks.com. The following website contains many useful, interesting links about SPM: http://www.ou.edu/research/electron/www-vl/afm.shtml.

Overview

Scanning Probe Microscopy (SPM) includes Scanning Tunneling Microscopy (STM), Atomic Force Microscopy (AFM), and a variety of related experimental techniques. These are experimental methods that are used to image both organic and inorganic surfaces with (near) atomic resolution. In a scanning tunneling microscope a sharp metal tip, terminating ideally in a single atom, is positioned over an electrically conducting substrate, and a small potential difference is applied between them. The gap between the tip and the substrate surface is made large enough that electrical conduction cannot occur; yet, it is small enough to let electrons tunnel (a quantum mechanical phenomenon) between the tip and the surface. Tunneling probability decays exponentially with increasing tip-to-surface separation. Thus, the spatial arrangement of atoms on the surface is determined by the variation in tunneling current sensed by the probe tip as it moves in atomic-scale increments across the surface, a process called rastering. Scanning is more commonly done by adjusting the tip-to-surface separation so as to maintain a constant tunneling current, thereby preventing the tip from crashing into the surface. In either mode of operation a "map" of the sample surface with atomic resolution results.
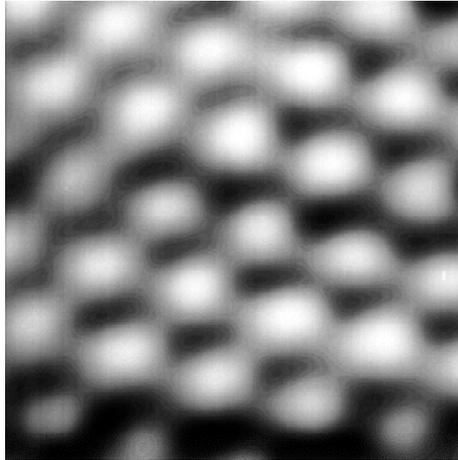
Figure 3. The STM image of a close-packed layer of Ag atoms. (Photograph courtesy of Robert Hamers.)

Atomic Force Microscopy (AFM)

In an atomic force microscope the surface topography is mapped by measuring the mechanical force between tip and surface rather than the electrical current flowing between them as the STM does. Since force is used to create the images rather than the electrical current, the AFM can be used to image both conducting and non-conducting substrates. To measure the interatomic force, the tip of the AFM is mounted on the end of a small cantilever. As the interatomic force varies, the deflection of the lever can be sensed by bouncing a laser beam off the back of the lever and measuring displacements with a pair of photosensors
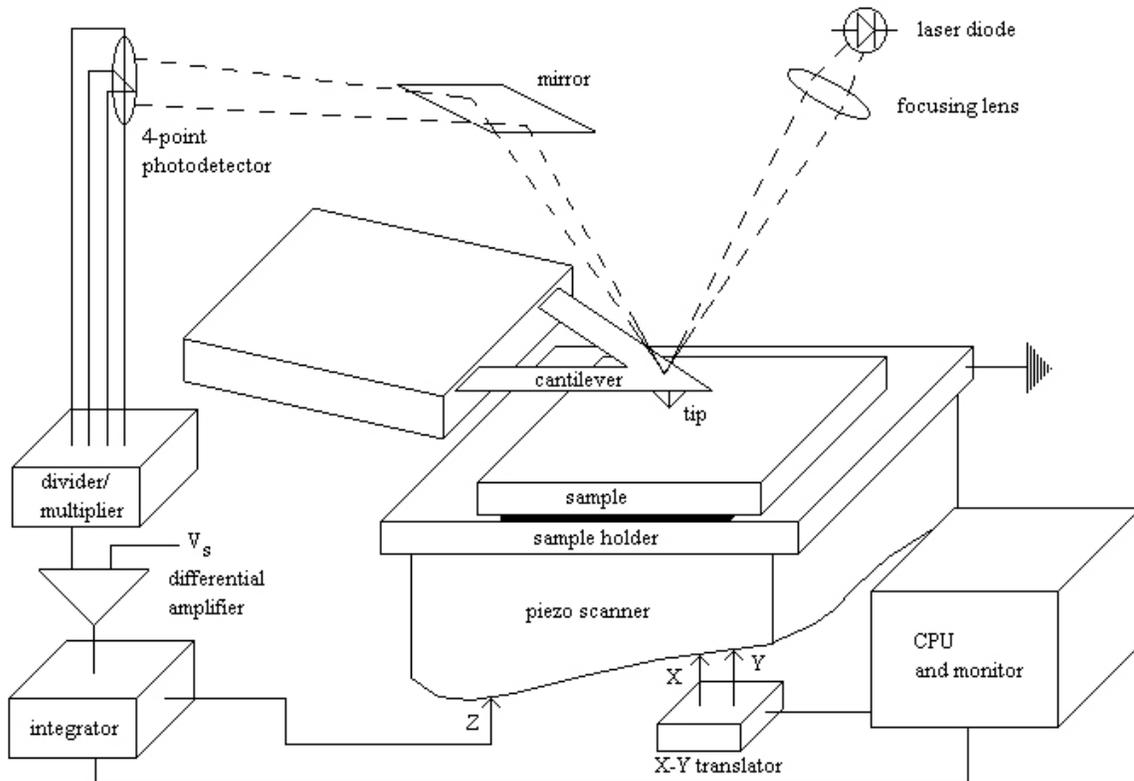
Figure 4. In AFM, small forces are measured between the tip and the sample during scanning. These forces cause vertical movement of the cantilever, which is monitored by a laser beam that is reflected from the top cantilever surface.

Electrons and the Scanning Tunneling Microscope (STM)

Gert Binnig and Heinrich Rohrer were awarded the Nobel Prize in Physics, in 1986, for the development of the scanning tunneling microscope. They were also jointly honored with Ernst Ruska for their work on the development of electron microscopy.

To gain a better understanding of how the scanning tunneling microscope works, the behavior of electrons in metals and other electrically conducting material needs to be considered. Electrostatic forces acting between the electrons and the nuclei of atoms hold the atoms of a metal together. Core electrons are bound tightly to individual nuclei. However, the valence electrons that are farthest from the nuclei feel a relatively weak electrostatic attraction and are free to move about in the space between the nuclei. Since these electrons carry or conduct the electric current, they are referred to as conduction electrons. The large numbers of valence electron orbitals overlap and provide a continuous distribution of states available to the conduction electrons, called a band, that extends over the entire solid. Each orbital can be occupied by a pair of electrons with opposite spin, and they are filled in order from lowest to highest orbital in energy. The Fermi energy (E_F) is the energy of the most weakly bound electrons. The electrons at the Fermi energy are held in the metal by an energy barrier. Classically, these electrons can never leave the metal unless they are given enough energy to go over this potential barrier. Quantum mechanically, however, electrons near the Fermi energy can tunnel through the potential barrier. By placing two pieces of metal close to one another, a finite square-well barrier can be created.
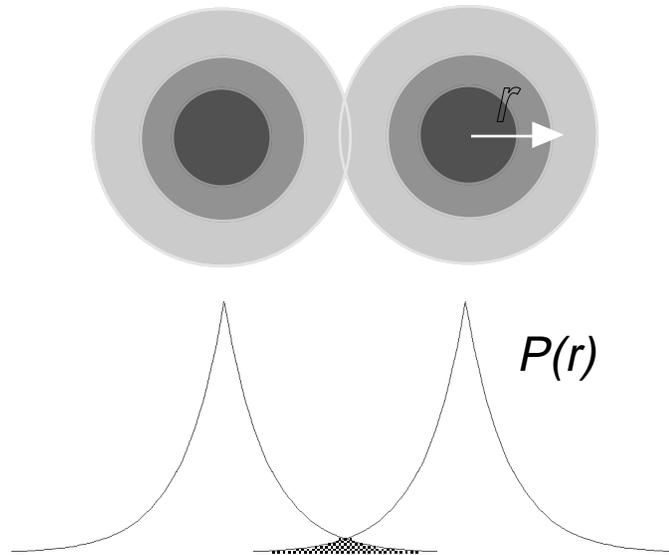
Figure 5. Two atoms with their electron probability clouds slightly overlapping. In the top part of the figure, the atoms are represented as spheres with overlapping volumes. In the bottom part of the figure, the graphical representations of the electron probabilities (as a function of distance from the nucleus) are seen to overlap.

Tunneling
The quantum mechanical phenomenon called tunneling is possible when the tip is only within a few angstroms (10^{-8} cm) of the surface. Tunneling is the term used to describe the movement of an electron through a classical barrier, which is possible only due to its wave nature and hence impossible in classical physics. To understand this better, consider only one atom. The electrons surrounding the atomic nucleus are not confined to a hard shell but are within a varying probability distribution. This causes the edges of the atom to be indistinct. When the quantum mechanical equations describing the probability of the electron locations are solved, it is found that the electron spends most of its time near the nucleus, and the probability distribution falls off exponentially as the distance from the nucleus increases. Because the electron probability distribution falls off so rapidly with distance from the nucleus, this tunneling current provides a very sensitive probe of interatomic separation. If two atoms are within angstroms of each other, an electron from one atom can move through the region of overlapping electron density to become part of the other atom's electron cloud.
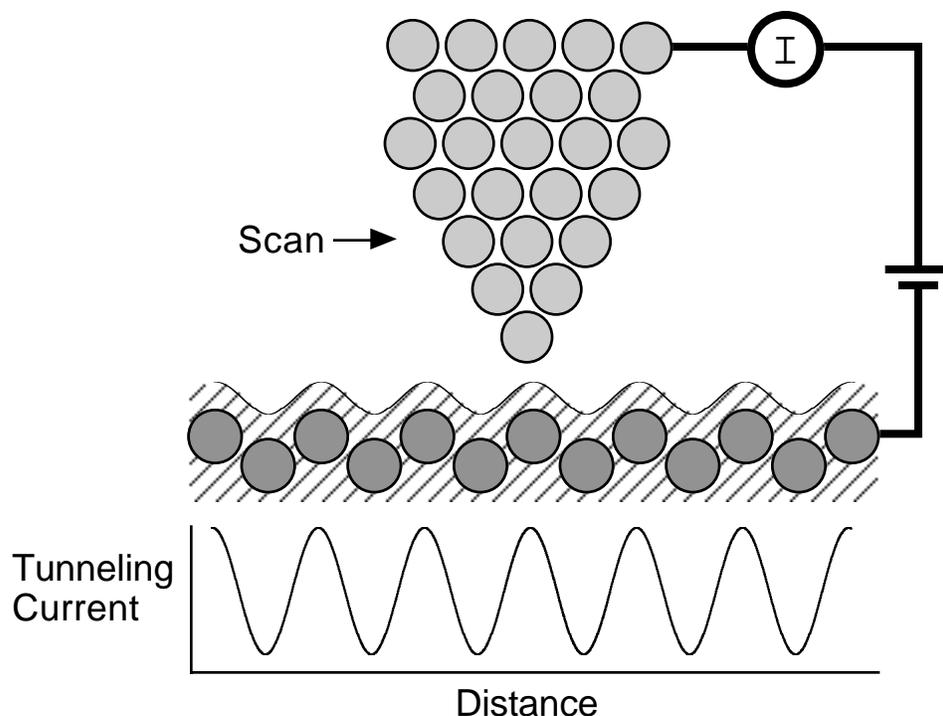
Figure 6. A plot of tunneling current as a function of horizontal probe tip position. The absolute vertical position is held constant. When the tip is nearest the surface atoms, the current is highest. The wavy line above the shaded circles represents the contour of the surface.

Challenges for STM
Theoretically, STM can be used to image individual atoms on the surface; in practice, however, three challenges arise. The first challenge is vibrations. Vibrations are important because the separation between the sample and probe is so small. Since the tip is only a few angstroms from the surface, it is easy to crash it into the sample unless the substrate is smooth on the atomic scale. For such a small separation, any minor perturbation such as vibrations set up by a sneeze or motion in the room can jam the probe into the sample and ruin the experiment. As a result, careful engineering is necessary to make the instrument rigid and to isolate it from external disturbances. Another problem, probe sharpness, determines how small a structure can be imaged on the surface. Electrochemical etching can be used to sharpen the end of a metal wire to a radius of about 1000 nm. A probe with such a large surface area would allow tunneling to occur over a large region of the sample surface. In order to detect individual atoms, the probe tip must be comparable in size to an atom. Thus, the probe tip must ideally consist of a single atom. The final problem is that of position control. In order to move the probe with controllable displacements of 0.1 nm (1 angstrom) or less, a special type of piezoelectric ceramic material is used. This material expands and contracts on a scale of angstroms when appropriate external voltages are applied to pairs of electrodes on its opposite faces. Therefore, a probe attached to a piece of piezoelectric ceramic can be moved with great precision by application of external voltages.

The STM Tip
The tip is prepared so that it terminates in a single atom. The tip is usually composed of tungsten or platinum. If the experiment is performed in a vacuum, tungsten is the preferred material because it is relatively easy to prepare a single-atom-terminated tip. If the STM experiment is to be performed in a liquid or in air, tungsten reacts too quickly. Therefore, Pt

or Pt-Ir alloys are preferred even though it is more difficult to prepare tips with these materials, and they generally are not as atomically sharp.
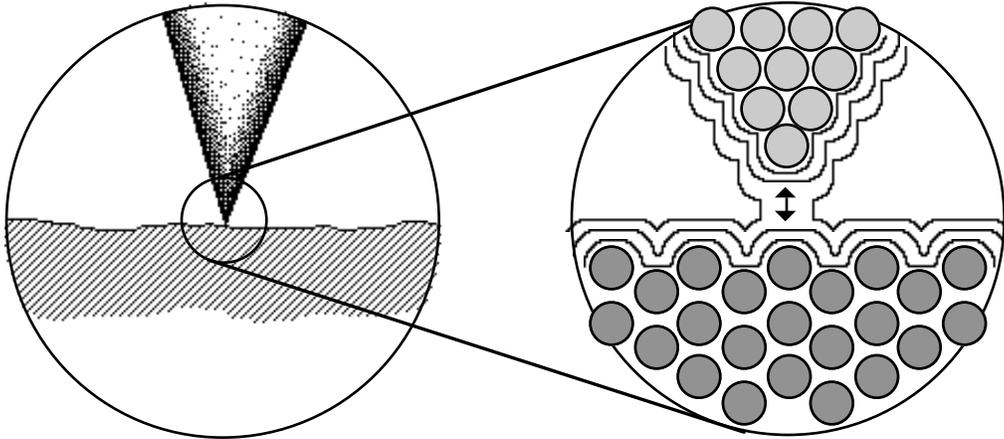

Figure 7. A sketch of an atomically sharp tip near a surface (left-hand picture) and a blow-up (right-hand picture) of the atoms of the tip (grey circles) and the surface (black circles).

Uses and Capabilities of STM
The STM has many uses. It is used in fundamental studies of the physics of atoms at surfaces. STMs can be constructed to be compatible with high-vacuum conditions, which are used to study the properties of atomically "clean" surfaces or surfaces that have been modified in some controlled way. The STM can also be used to study electrode surfaces immersed in liquid electrolytes. In addition to these scientific applications, the STM has a wide range of potentially practical applications. The STM can image structures ranging from DNA in a biological environment to the surface of an operating battery electrode. The application of the STM to biological molecules has been proposed as a method of gene sequencing. Research is currently being done to demonstrate the ability to write with atomic resolution. Features a few nanometers wide have been written by using the probe to scratch or dent the surface directly or by using the tunneling current to locally heat the surface of a substance. The probe has even been used to move individual atoms so as to form a word. Scanning tunneling microscopy is a practical demonstration of quantum mechanics. Scanning probe microscopy techniques may be used to create atomic-scale devices and new structures. For example the STM has been used to prepare a "nanobattery," which consists of two copper pillars and two silver pillars that are placed sequentially on a graphite surface by electrochemical reduction of solutions of copper sulfate and silver fluoride.
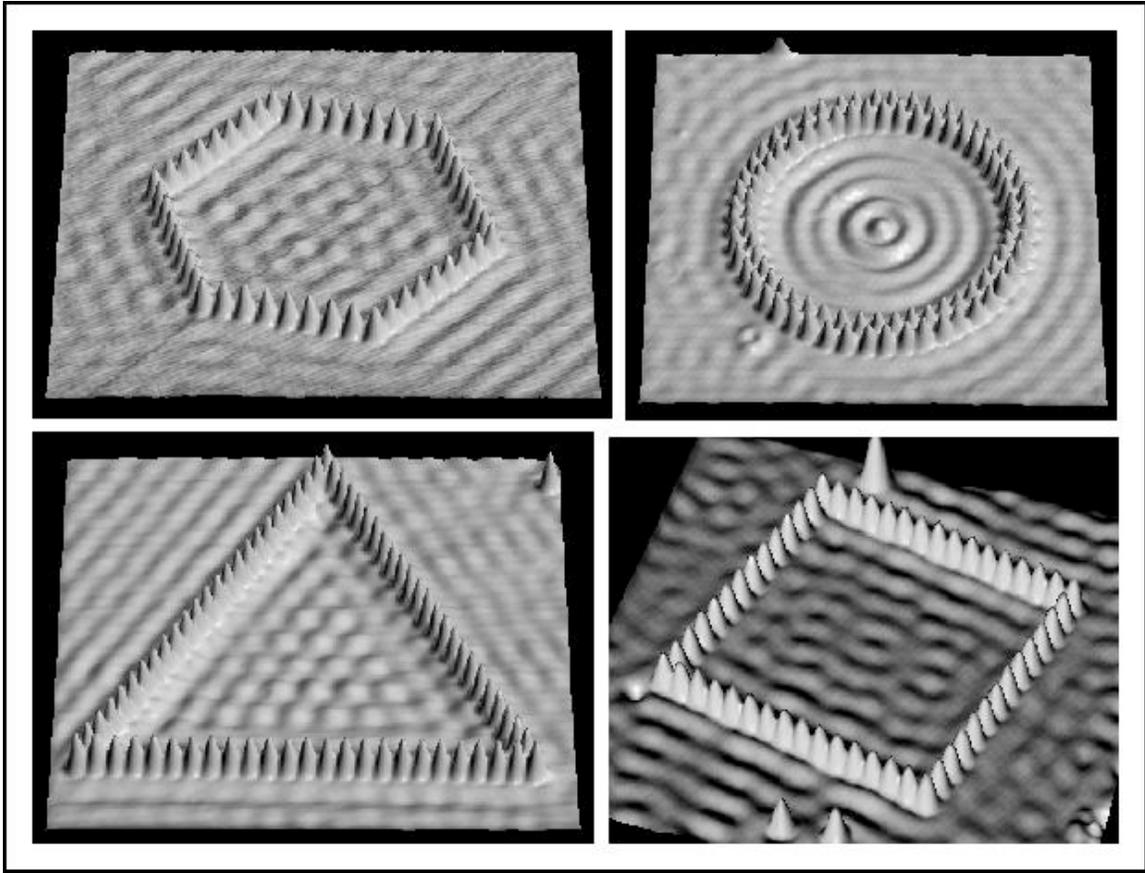
Figure 8. An example of the images that can be made with atoms using Scanning Tunneling Microscopy. The images shown are of iron atoms on copper.

Expected Outcomes

Students will be able to describe the basic process of remote imaging and to explain why remote imaging is important and useful. Students will able to match numerical data with visual images. Students will be able to explain at a rudimentary level how Scanning Probe Microscopy works.

Materials

marble (optional)

empty fish tank or large clear container(optional)
shoeboxes (one for each 2-3 students)
pre-fabricated plastic landscapes or homemade landscapes (Plaster of Paris or household objects)
copies of Unknown Surface Grid (one for each box)
Pick-up sticks or small straws
metric rulers (one per group)
calculators (optional)

copies of Data Sheet#1, Transforming Data, Data Sheet#2, and Data Analysis Sheet (one per student)
colored pencils, markers, or crayons
8 _"X11" pieces or poster board or card board
school glue or glue gun
mini-marshmallows (1 bag per group)
access to Microsoft Excel (optional)

Procedures

1. Before class, assemble "mystery boxes" using the shoe boxes. Inside each shoebox, create a miniature landscape. Landscapes should be made with hard material that cannot be poked through easily. Prefabricated plastic landscapes used to teach topographic mapping can be used. Other materials like Plaster of Paris and aluminum foil, various size pieces of wood stacked on top of one another, miscellaneous household objects like bottles, cans, and small boxes can also be used to create mystery landscapes. These landscapes should constructed and secured inside the boxes, and the boxes should be taped shut so students cannot see the mystery landscapes.

    Unknown Surface Grids should be taped or glued on to the box top. Holes should be punched through the shoebox lid at dot in the middle of each square with a compass. If used properly, boxes should be reusable year after year.

2. Discuss with students the following questions "How did we get pictures of Venus' surface even though its cloud cover is so thick that we couldn't take a photograph of the surface?" and "How do we have maps of the ocean floor when even though we can't see the ocean floor from the surface?" and "How do bats know where insects are in the dark?"

3. This discussion gives the teacher an opportunity to introduce the concept of remote sensing and imaging.

    These technologies can be easily demonstrated to students. One way is to have all students close their eyes. The teacher drops a marble for a distance above her head, lets it bounce asks, "Did I drop the marble from up high or down low?" The procedure it repeated again, except that the marble is dropped from a distance of about 1 foot from the floor. The clicking sound of the marble hitting the floor indicates if the teacher's hand was close to or far away from the floor.

Another way to visualize these ideas is to imagine throwing a ball at a wall while blindfolded.   If the ball came back quickly, the person must be very close to the wall. If it took some time for the ball to return, it would indicate that person must be some distance away from the wall.

4. Another way to demonstrate these ideas using data is create a small landscape in a dry fish tank. The landscape can be made of sand, salt, various containers, or even crumpled paper taped into place. The landscape should have very high and very low points.
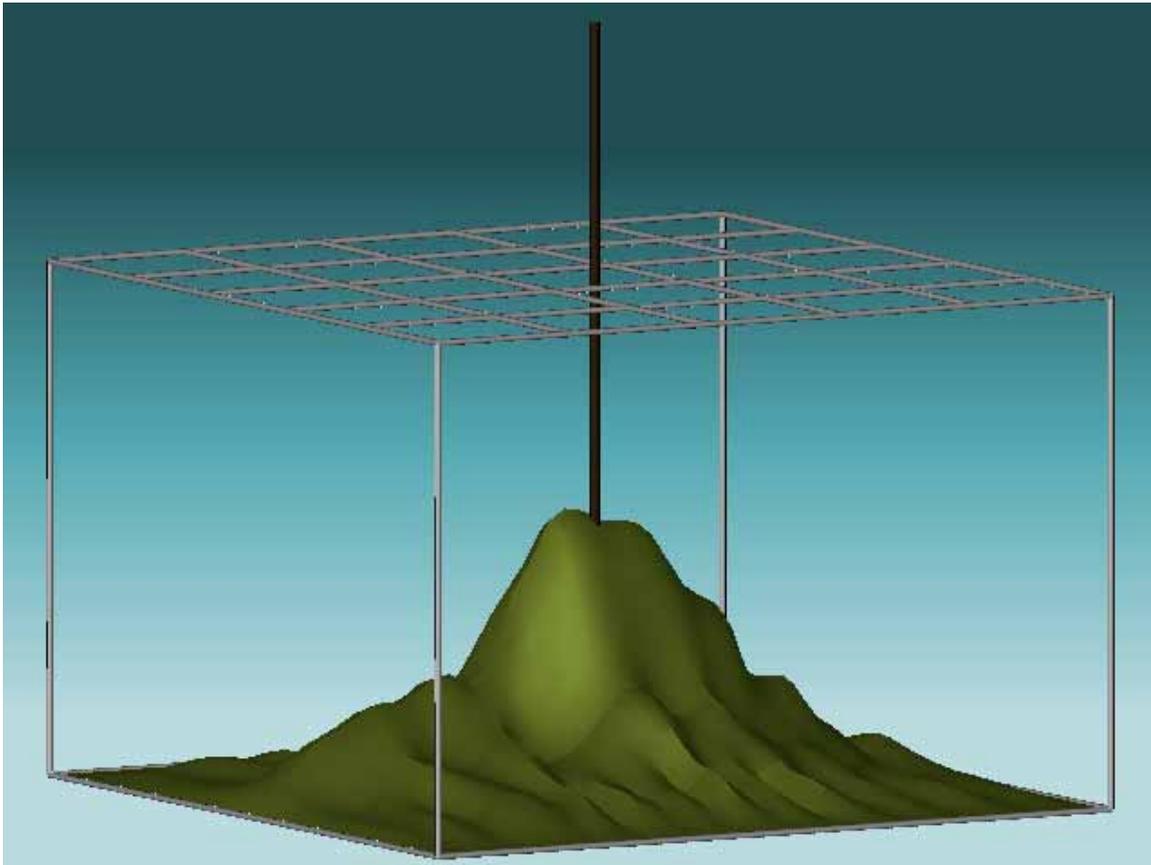
A simple grid on a piece of cardboard placed across the top of the fish tank and ruler can be used to demonstrate how data could be systematically gathered.

5. Now that students have had an opportunity to see how data can be gathered, students are ready to gather data to figure out what the landscapes inside their mystery boxes are. Students should use "pick-up sticks" or small straws to measure the distance (to the nearest centimeter) the depth of the mystery landscape (distance from the top of the box to the landscape). To measure the depth, students should push their sticks into the hole just until they feel the stick hit the surface of the mystery landscape. Students should hold or mark the stick with a pencil, remove the stick, and then measure the height with a metric ruler. They should record the data on Data Sheet#1.
6. Students should read and complete the Transforming Data sheet. Teacher and students should discuss why the data needs to be transformed. Probably the easiest

way to transform the data is to find the height of the box and subtract each point's depth from the height of the box. This will yield each point's height.

7. Students should complete the original Data Sheet#2 and the extra copy DataSheet#2 with the "transformed" data.

8. Before having students begin step 9, the teacher should model how to analyze the transformed data and how to form a mental picture using the data. A Teacher Sample Transformed Data Sheet with sample data is provided form demonstration purposes. This sheet should be made into a transparency. It should be color coded with overhead markers so that each height is a different color. With the teacher's guidance, the class can analyze the features of the map before attempting to analyze their own maps.

9. Students should complete Part I of the Data Analysis sheet. Students are asked to color code all the data on the original Data Sheet#2. Coloring all the points of the same height using the same color will help to highlight variations in the landscape and should help students begin to form a mental image of what the landscape looks like. Students should share their insights and ideas with the teacher and other students before moving on to the next step.

10. When students have finished coloring and forming mental images based on the data, students should begin constructing the mini-marshmallow model of the landscape with the members of their group. Since each mini-marshmallow is about 1 cm in height, students can construct a fairly accurate model of the landscape by gluing the appropriate number of marshmallows on each square of the extra copy Data Sheet #2. For example, three marshmallows should be glued on top of one another on each square that contains the number three. **Tips:** Teachers may want to model building a surface with marshmallows before students do their own. Also, Extra copy Data Sheet#2 should probably be taped or glued to poster board or cardboard before gluing begins. Marshmallows that have been left out of the bag for a day or two in a dry place will dry up and be easier to use. For ease of construction, students should begin gluing in one corner and move out slowly from that corner to avoid bumping into and knocking over stacks of marshmallows.

11. Students should have a chance to see the completed landscapes of others and then should complete Part II of Data Analysis.

12. If Microsoft Excel is available, enter the data into the spreadsheet. {Give specific directions for using Excel here.} Students should then complete Part III of the Data Analysis.

13. Students should be able to open their landscape shoeboxes and compare their models to the original. They should complete Part IV of Data Analysis.

14. At this point, it is important for students to begin to understand that sensors and computers that form remote images use these same basic steps. While the probe they used was a Pick-Up Stick and a ruler, scientists may use sound waves and sound detectors or radio waves and radar detectors for their probes. In the case of Scanning

Probe Microscopy, scientist may use electrical current and resistance detectors and very sensitive force detectors. See **Teacher Background** information above for more detail. Computers are used to record the data (something the students did by hand by recording the heights on a grid) and to construct a 3D image (which students did with marshmallows and Microsoft Excel).

Extensions

15. This activity would fit well with the use of the Exploring the Nanoworld Kit which includes the use of a refrigerator magnet to demonstrate the function of Scanning Probe Microscopy. This demonstration is most analogous to the Magnetic Force Microscopy technique.

16. If at all possible, build and demonstrate the Lego Magnetic Force Microscope. Plans are available at http://mrsec.wisc.edu/edetc/LEGO/index.html.

17. Another possible extension is to build a simple model of Scanning Probe Microscopy using a multimeter that can be found at http://mrsec.wisc.edu/EDETC/modules/xray/Investigation3-Student.pdf.

18. Arizona State University through Interactive Nano-Visualization in Science and Engineering Education (IN-VSEE) (http://invsee.asu.edu/invsee/invsee.htm) offers opportunities to submit samples for viewing with SPM technologies as well as an excellent gallery of images produced through SPM techniques.