Investigating Static Forces in Nature: The Mystery of the Gecko
Lesson 7: How Do We Measure Forces at the Nanoscale Level?
Elaborate

Student Learning Objectives:

- Compare and contrast model probe instruments with those that are used to make measurements of electric and magnetic forces at the nanoscale (AFM, MEMS)
- Model how instrument probes can be used to characterize surface interactions
- Describe how the topography of a surface relates to adhesion
- Interpret graphs of forces at the nanoscale level
- Consider the new evidence about surface topography and seta adhesive forces to evaluate remaining methods of gecko adhesion

At a Glance for Teachers:

- Activity: Topography of the Unknown—Simulate how a probe characterizes an object by converting numbers into an image
- Activity modeling an AFM with refrigerator magnet
- View a short video about the atomic force microscope
- Compare and contrast box probes with the atomic force microscope
- Teacher demonstration: how gecko setae tips fill in the spaces on a simulated smooth surface
- Interpret force graph of a single gecko seta as measured by a MEMS device

<u>Note: Some questions in the Student Journal are underlined as formative assessment checkpoints for you to check students' understanding of lesson objectives.</u>

Estimated Time: 90 Minutes

Vocabulary: Atomic Force Microscopy, Cantilever, Characterization, Integrated Circuit, Micro-Electro-Mechanical Systems (MEMS), Nanotechnology, Newton, Probe
Refer to the end of this Teacher Guide for definitions.

Materials:

- PowerPoint for Lesson 7
- Student Journals for Lesson 7
- VCR or computer with LCD or overhead projector
- Video “Atomic Force Microscope” http://www.mcrel.org/nanoleap/multimedia/index.asp

For Each Team:

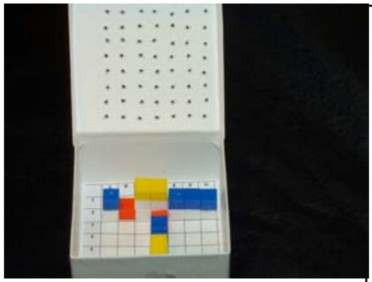
- 4x4x2 inch cardboard box with lid
- One white vinyl coated paperclip
- Fine tipped permanent markers (three colors)
- One centimeter plastic cubes
- Glue
- Scan paper (grid found in Student Journal page 7–2)
- Refrigerator magnet (and a magnetic strip to serve as a probe)
- Access to computers with Excel software

Part 1: Advanced Preparations for Activity—Probing the Unknown: Topography of the Unknown

Note: It will save class time to have one box pre-made for each group of students.

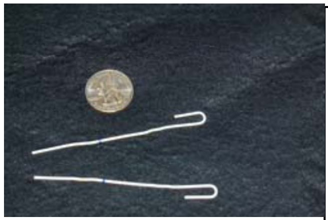
Image 7.1

1. Choose a side of the box lid and mark it with a “T.” Choose a side of the box and mark it with a “T.” Line up the two “T’s,” (lid and box) and this will be the top of your box when the lid is on the box.
2. Place one piece of scan paper on the lid of your box. Make sure the row of letters is at the top (along your “T”), and the column of numbers is along the left of the box. Tape it down.
3. Cut off the excess paper. Secure the paper with tape or glue.
4. On the box lid **only**, use a thumbtack to pierce a hole in the center of each square on the scan paper.



5. Open the box and place a new piece of scan paper at the bottom of the box. Make sure the row of letters is at the top (along the “T”), and the column of numbers is along the left side of the box. Tape it down.
6. Cut off the excess paper. Secure the paper with tape or glue.
7. Stack the cubes at three different heights and glue them down.
8. Place the box lid back on the box so that the “T’s” on the top of the lid and the top of the box are lined up.

Image 7.2



9. Straighten one end of the paperclip.
10. From this straightened end, measure and mark with permanent markers:
    - two centimeters from the tip, with one color marker
    - three centimeters from the tip, with a second color marker
    - four centimeters from the tip. with a third color marker
11. Make sure you encircle the entire circumference of the paperclip.

Image 7.3 (top)
Image 7.4 (bottom)

Part 2: Demonstration—Modeling Setae Size and Filling in the Spaces

Background:
As students learned with the activity involving the shoes and charcoal dust, there is a significant difference between real and apparent contact between surfaces. Solid surfaces are rarely completely smooth (planar) and when observed up close, have a very definite topography. Therefore, real contact area only includes the places where surface of an object comes into actual contact with a surface terrain.

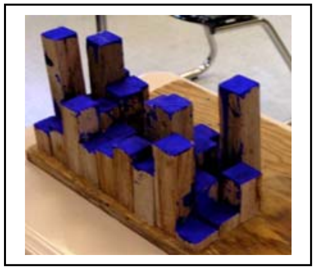
In this activity, students will have an opportunity to observe how a gecko seta's spatula-shaped tips, which in actuality are about 100-200 nanometers in width, allow them to adhere to apparently smooth surfaces. Students will view a demonstration of a model of a surface terrain and a model of the spatulas on a gecko seta in order to experience how size characteristics of the seta and their ability to comply allows for a large amount of real contact with a surface terrain.

Goal:
In this activity, students will view models of different configurations of gecko spatulas in order to model the effect of the number of spatulas on surface contact.

Advanced Preparation for Part 2: Demonstration—Modeling Setae Size and Filling in the Spaces Activity

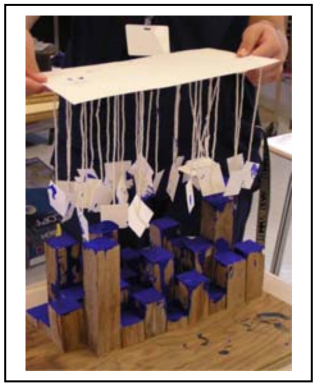
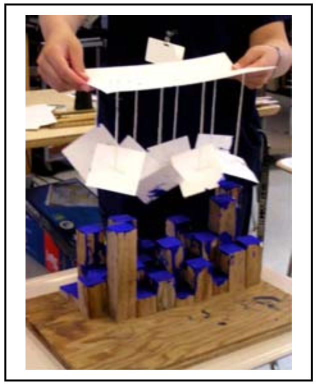
Create several models of the three-dimensional surface terrain**. Be sure to make the terrain varied**. Remember, few surfaces are really flat!

Materials:
- Wooden blocks to make a three-dimensional terrain (like a relief map)
- Four 5x8 inch index cards (one to model the surface terrain, three to suspend the spatulas)
- One 5x8 inch index card to be used as a pattern for modeling spatulas
- Paper to model gecko spatulas
- Glue
- Scissors
- String
- Tape

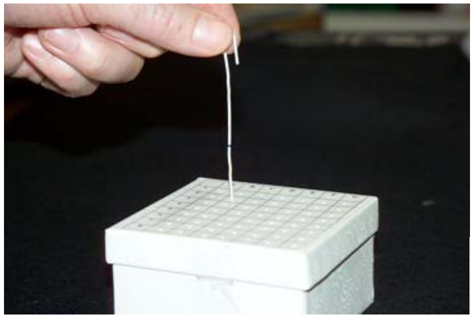


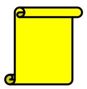
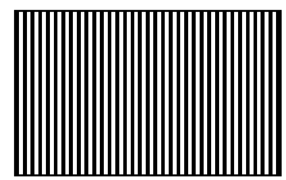
Creating the Models of the Gecko Seta

1. The model will be made up of paper suspended by string on card stock.
2. Determine the number and size of the spatulas you will be creating (see PowerPoint slide 8).
3. Measure the length and width of the seta on paper and cut out the correct number for your model.
4. Attach the spatula tips to string using tape on the very middle of each seta.
5. Attach the string to the index card or card stock using tape.


Slide # Student Journal Page #	*Teacher Background Information and Pedagogy* **"Teacher Script"**
Slide 1 Title	1) *In the activity "Probing the Unknown: Topography of the Unknown," students will characterize a surface up close. Advanced preparation includes assembling the observation boxes with a surface terrain made up of centimeter cubes. The students will use height probes to determine the surface height of the surface topography. After recording the height variations, students will create topographic maps of the surface using an Excel spreadsheet. Using these maps, students will analyze the data and the instrument used to collect the data.* Part 1: Probing the Unknown **"In this lesson, we will be investigating how nanotechnology instrumentation can be used to better understand the natural phenomenon of the gecko adhesion."**
Slide 2 Student Journal Page: 7–1	2) *Discuss probes you have used in the physical science class. Include in the discussion how the probes have helped you identify properties of objects. In other words, these probes have helped you characterize objects.* **"What are some instruments (probes) that you have you used in previous science classes?"** *Students in the field test often included general materials such as glassware and Bunsen burners in their responses. Guide students to identify common probes such as a magnifying glass, a microscope, a telescope, a spring scale, litmus paper, a stethoscope, and computer probeware.* *Introduce the pre-made boxes for the activity.* **"We will begin by using a model to understand how surfaces can be characterized without being seen. Inside these boxes, I have a unique object. I can't see it. I can't feel it, yet I want to know something about it. Scientists use probes to characterize matter that we can and cannot see."**
Slide 3 Student Journal Pages: 7–1 7–2	**"Today, we are going to use a straightened paper clip as a probe to determine the topography of a surface we cannot see."** **"The image on this slide shows a top down view of a paperclip being inserted into a box to determine the shape inside the box. We are going to characterize the surface in each box. Then, you will make a scan of its appearance."** 3) *Have students write a procedure in their journals as you explain how to complete each step. For the first class using the boxes, demonstrate how to safely make the holes on the top lid using a thumbtack. Pierce the center of each square of the scan paper that is attached to the lid if it has not been previously done. Model how to insert the probe into the box.*

	Emphasize the importance of measuring straight down.  4) *Once students can use the probe and understand how to measure the height of the object, proceed. Direct students to* ***systematically*** *measure and record the height of the surface at all probe holes.* 5) *Students can work in teams of between two and four students per group. Encourage each student to probe, measure, calculate, and record so that each student has the complete experience.* 6) *When recording the measurements, students should record on the scan area provided on page 7–2 of the journal or on an additional scan paper. If a student calculates 3 cm on the lid, grid A5, they should find A5 on the scan paper, and write 3 cm.*
Slide 4 Student Journal Page: 7–3	**"You will be following the directions in the Student Journal and using an Excel spreadsheet to create a three-dimensional representation of the objects in your box."** 7) *Optional: Once students are done, have them complete the analysis question in their journal. Then allow them to view what's inside of the box. Comparison with the actual arrangement in the box is very important as well. It provides a visual reminder of the uncertainty inherent in any such indirect process. The instrument can be counted on to reveal some information about the surface topography, but there is always uncertainty; it is never an exact replica. If you allow students to look at what is in the box, remind them that in a real situation, they can never "actually open the box and see what's really inside." In this case the students are constructing a model of the surface topography; models are never exact replicas.* *To save time, a field test teacher entered one student's data into the Excel spreadsheet to demonstrate how the numbers*

	translate into an image and displayed it via Smartboard™. *Atomic Force Microscopy is often used to map out the topography of surfaces at the nano level. The probe can be small enough so that the end of the tip is a single atom. The distance between the tip and the surface is the thickness of a couple of atoms.* *Optional: Have students print and staple their graphs to their journal.*
Slide 5 Student Journal Pages: 7–3 7–4 	**"Atomic Force Microscopy is an example of a scanning probe microscope. In scanning probe microscopes, a tiny probe moves across the surface of the test materials. In Atomic Force Microscopes (AFM), cantilevers are used to detect surface <u>topography</u> by measuring attractive or repulsive forces between the tip and the surface to reveal the surface roughness of seemingly smooth surfaces. This model helps demonstrate the nature of the surface to which the gecko is adhering."** *8) Show a short video "Atomic Force Microscope," available at: http://www.mcrel.org/nanoleap/multimedia/index.asp or on the CD. The video demonstrates how an Atomic Force Microscope or AFM is used to image the surface of a DVD.* *9) As students watch the video, have them answer the following questions:* *1. What does AFM stand for?* *2. What does the AFM do?* *3. How does the AFM do it?* *10) Distribute refrigerator magnets and magnetic probe strips to each group of students for the AFM modeling activity. For their drawings, ask them to draw the forces as looking from the top down. As a follow-up discussion, ask students to consider:* **"How does the distance from the probe to the surface affect the force that is measured?"** *Using the magnetic probe, the students should explicitly note that the closer the probe is to the surface, the greater the force that is measured.*  *Student drawings may include alternating bumps on a surface. See example at right:*
Slide 6 Student Journal Page: 7–4	*11) Have students use the comparison matrix on page 7–4 of the Student Journal to compare and contrast two or three characteristics of the AFM as described in the video and the model height probes used in class. (See Appendix A for possible answers.)*

Slide 7	**Part 2: Demonstration: Modeling Setae Size and Filling in the Spaces** *12) Explain to students that in this demonstration, you will be modeling how the spatulas on a gecko's seta come into contact with a surface. Emphasize that the surface topography being portrayed in this model is exaggerated in order to view how the spatulas interact with the surface.* *A field test teacher asked students to build their own models.* **"Question: How do gecko spatulas of a seta affect the amount of surface contact?** **Prediction: How do you think the number of spatulas will affect the amount of contact between the gecko and the terrain?"**
Slide 8 Student Journal Page: 7–5	**"Each seta model can be lowered onto the terrain. Make observations about the amount of opportunity for contact that occurs for each test."** *The first image shows an example of how a surface might be constructed. The second image shows a model seta with one large spatula. The third image shows a model seta with four spatula-shaped tips. The last image at right shows a model seta with twelve smaller spatula-shaped tips.*
Slide 9 Student Journal Page: 7–5	**"This image shows a compliant surface on a hard surface. How is this image similar to what was modeled in the teacher demonstration? How is it similar to the transparent tape on table activity?"** *13) This model demonstrated how surfaces can come into very close contact. The transparent tape must have the characteristics of a liquid. Without having liquid properties, the gecko seta has many spatula-shaped tips that can get into the nooks and crannies of a surface.* **"Remember from the AFM (magnetic probe, slide 5 and video), the closer the probe is to the surface, the greater the force that is measured."**
Slide 10 Student Journal Page: 7–5	**"These artist's sketches illustrate two views of the spatula-shaped tips on a seta in contact with a rough surface like a wall. How are these drawings similar to the demonstration? How are they different?"** *The sketches are similar to the demonstration in that the spatulas in both come into contact with the nooks and crannies of the seemingly smooth surface. However, the model with the cubes showed a much rougher surface than what is shown in the sketches.*
Slide 11 Student	**"How does the number of model spatulas on a gecko seta affect the opportunity for surface contact?** **Based on what you observed about the gecko seta at the nanoscale level on slide 8, how does this model**

<table>
<tr><td>Journal
Page:
7–5</td><td>demonstrate the amount of opportunity for contact that the spatulas have with a surface?”

14) Refer students to slide 7 for the chart including adhesion methods from Lesson 5.</td></tr>
<tr><td>Slide 12</td><td>Teacher Background:
MEMS stands for Micro-Electro-Mechanical Systems. These mechanical structures are made using the same type of equipment (mechanical elements, sensors, actuators, and electronics on a common silicon substrate) that is used for Integrated Circuits. Many MEMS sensors detect signals by detecting a physical force. The device measures force two ways. One is the vertical force down onto the sensor. The second is the lateral force.

15) Display slide 12
“Researchers at Stanford Nanofabrication Facility used a special technology called MEMS (a horizontal force probe) to measure the adhesive force of a single gecko seta. MEMS stands for Micro-Electro-Mechanical Systems. In this image, one gecko seta is seen on a MEMS device prior to it being pulled to the side in order to measure the adhesive force.

What force units do you think a single gecko seta would have? microNewtons? nanoNewtons?”

Accept all student responses before proceeding to Slide 13.</td></tr>
<tr><td>Slide 13

Student
Journal
Pages:
7–6
7–7</td><td>16) Display slide 13.
“The following graph represents the adhesive force measurement of a single gecko seta. The seta was placed on the tip of a triangular cantilever and dragged across the probe laterally in order to measure the force between the seta and the probe as the seta slides across the probe and is removed from the cantilever.”

“What is being shown on the X-axis and Y-axis?”
“What units are being used?”
Y-axis shows the sensor output force measured in microNewtons. X-axis shows the time measured in seconds.

“Based on the graph, describe what is happening to the force between the seta and the cantilever as time goes by.”

17) For the last question, you may need to use the following prompts:

“What is happening between points A and B?”
This is where the sliding begins. Students might say that the force stays the same for two seconds, then increases at a high rate for two seconds.</td></tr>
</table>

	"What is happening between points B and C?" *Students should note that the adhesion has reached a maximum force and stays constant.* *Students may note that the seta appear to be coming off the probe surface as the seta approaches point C.* **"Describe what is happening between points C and D."** *Students should note that the seta slides off the probe surface by point D. They should observe that the force decreases at a high rate and drops down to zero.* *18) To help students interpret the graph, you may want to ask questions like:* • **"What is the maximum force that is measured for adhesion?"** *(About 180 microNewtons)* • **"Knowing that there are 1 million setae on all four feet, is this enough force to hold up a 2.2 Newton gecko?"** *(Yes! 180 µN * 10^6 =180 N)* • **"What questions do you have about this lateral force curve?"** *(Student answers will vary.)* *Optional:* *Some students will notice that the initial force measurement is less than zero. Ask them to consider why the force measurement begins at less than zero microNewtons? (Perhaps due to pressing the seta onto the sensor)* *Note: From Liang, Autumn, Hsieh, Zesch, Chan, Fearing, Full, Kenny[1]:* *43.4 N average sustained clinging force of gecko with 227.1 mm² pad area*
Slide 14	**"The maximum force presumably is reached when nearly all of the spatulas are in contact with the sensor surface. Initially unattached spatulas can be pulled into contact with the surface by their neighbors through sliding. Most importantly, adhesion increases significantly if the seta is dragged a short distance across the surface. All these can be attributed to the increase in number of spatulas that come in contact with the surface..."[2]** *19) You might want to model this again using the seta demonstration from earlier in this lesson. You can use the analogy of a string mop across the surface model (from slide 8) to illustrate this phenomenon. When the strings on a mop are*

[1] Autumn, K., Liang, Y. A., Hsieh, S. T., Zesch, W., Chan, W. P., Kenny, T. W., Fearing, R., & Full, R. J. (2000). Adhesive force of a single gecko foot-hair. *Nature*, 405, 681-684.

[2] Autumn, K., Liang, Y. A., Hsieh, S. T., Zesch, W., Chan, W. P., Kenny, T. W., Fearing, R., & Full, R. J. (2000). Adhesive force of a single gecko foot-hair. *Nature*, 405, 681-684.

	unorganized, they would have less force when pressed to a surface than if the mop strings were all lined up and in the nooks and crannies. Remind students of the experiment they did using the spring scale to pull a piece of tape off the surface on which it was stuck? Although the students didn't quite pull the scale horizontally, they could imagine having done that.
Slide 15	*20) As a discussion, ask students to respond to the questions in "Making Connections."* **"How are AFM and the MEMS devices used to help understand gecko adhesion?"** *Students should understand the difference between AFM, which is used to image the surface of an object, and the MEMS, which are used to make force measurements.* **"What do we now know about the amount of force between a single seta and a surface?"** *Based on information from this graph, the seta provides 180 µN of force; the one million setae on all four feet provide 180 N. This is more than enough to hold up a 2.2 N. gecko.* **"How does this new information help us understand the adhesion method for the gecko?"** *Evidence from the graph indicates that there was smooth sliding with the removal of the gecko seta, which is similar to removal of tape from a surface. Capillary wet adhesion has been ruled out because geckos do not leave a wet trail. Electrical forces similar to tape require a liquid property not found on the gecko setae.* **"What should we explore next?"** *An intermolecular electric force that does not involve a liquid adhesive (Capillary Wet Adhesion) is needed.* **"We will investigate the nature of the forces involved in gecko adhesion and 'solve' the mystery in the next lesson."**
Slide 16	*21) The pilot-test teachers highly recommend using this flow chart at the end and/or beginning of each lesson. The end of each lesson contains this flow chart that provides an opportunity to show students the "big picture" and where they are in the lesson sequence. The following color code is used:* *Yellow: Past Lessons* *Blue: Current Lesson* *Green: Next Lesson* *White: Future Lesson*

Before Lesson 8 ☆	*During pilot tests, teachers said that students benefited from a review of atomic structure prior to Lesson 8. Those physical science teachers that taught chemistry before physics concepts in their course sequence found that the concepts for Lesson 8 were much easier than those that taught the physics concepts first.* *For a review of basic atomic structure, you may use your normal curricular resources. A brief PowerPoint included on the CD based on a module found at the following Web site can also be used to review these concepts:* http://genesismission.jpl.nasa.gov/educate/kitchen/techappl/index.html http://genesismission.jpl.nasa.gov/educate/scimodule/UnderElem/index.html

Appendix A: Answer Key for Comparison of AFM and Box Model (Slide 6)

	AFM	**Box Model**
What characteristic is measured by the probe?	*Surface topography*	*Height of object in box*
How is this measured by the probe?	*By measuring the forces that change with distance between probe and surface*	*By direct contact of probe to surface*

Appendix B: NanoLeap Physical Science Vocabulary for Lesson 7

Atomic Force Microscope (AFM)
A type of scanning probe microscope in which a probe (usually a small cantilever with pointed top at the end) moves across the surface of a nanoscale object in order to measure surface properties, especially interactive and repulsive forces and the topography

Cantilever
A device used to detect and measure the amount of attraction or repulsion of the surface of an object

Characterization
The act of distinguishing or describing traits, qualities, or properties

Integrated Circuit
A tiny fabricated complex of electronic components, such as transistors, and their electrical connections, that is produced in the surface region of a small slice of material such as silicon (also called a silicon chip or computer chip)

Micro-Electro-Mechanical System (MEMS)
A small micro-machined device that combines electrical and mechanical elements at the micro or nanoscale to either sense or measure something (such as forces), to actuate something (cause motion, for example) or both

Nanotechnology
1. Manipulating materials on the atomic or molecular scale
2. The science of manufacturing materials and machines at the nanometer scale

Newton
A unit of force needed to change the speed of a kilogram of mass by one meter per second for every second that the force is acting on the mass

Probe
1. An object that is inserted into something so as to test conditions at a given point
2. A device used to penetrate or send back information