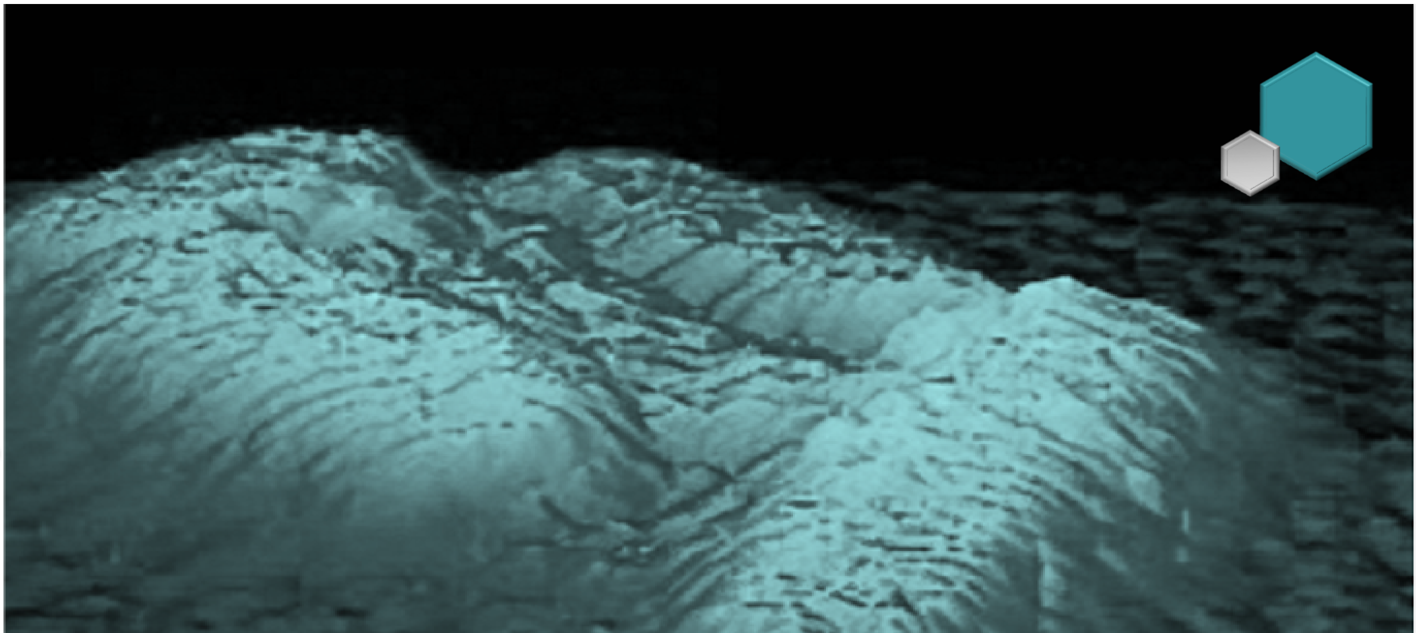
PHYSICS: Atomic Force Microscopes

How does an Atomic Force Microscope work?



PARTS 1: Understanding How Forces Impact Cantilevers & Springs

Image Credit: SAtomic Force Microscope Image, Eschericia coli--. C.J. Kazilek, Arizona State University. (2001). https://www.nsf.gov/news/mmg/mmg_disp.jsp?med_id=51835&from=search_list

Files Included for this Activity	5E Lesson Plans	Activity Lab Sheets*
PART 1: Understanding How Forces Impact Cantilevers & Springs	√	√

*The activity Lab sheets are located at the end of this document.

Additional Files Available for this Series	5E Lesson Plans	Activity Lab Sheets*
PART 2: Hooke's Law: Calculating the Relationship Between Deflection & Applied Force in Cantilevers	√	√
PART 3: Instrument Design: Understanding How AFMs Use Optics & Reflected Light to Determine Sample Properties	√	√
PART 4: Instrumentation Design: Statistical Analysis with Instrumentation	√	√

This module was developed by Professors Vernita Gordon and Alexandra Eusebi, with assistance from research & UTeach intern Khusbu R. Dalal, at the University of Texas, Austin, with funding provided by the National Science Foundation, Division of Civil, Mechanical, and Manufacturing Innovation, award numbers 1727544 and 2150878, to Vernita Gordon.

If you use any part of this module, please send an email describing your experience to Professor Gordon, gordon@chaos.utexas.edu. Please include the approximate number of students taught. Documenting this module's use and effectiveness will help us obtain more funding for outreach and education in the future.

LESSON PLAN: Atomic Force Microscopes

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Driving questions for lesson:
What are AFMs and how do they use forces to image surfaces on the nanometer scale?

PART 1 Understanding How Forces Impact Cantilevers & Springs	• How do Atomic Force Microscopes use forces to map surfaces? • How do forces impact a cantilever's movements?
PART 2 Exploring Hooke's Law with the Deflection of Cantilevers	• How can we describe a cantilever system with Hooke's law? • How can we use mathematical models to describe a cantilever?
PART 3 Instrumentation Design: How AFMs Use Incident & Reflected Light	• How are angle of incidence and angle of reflection used to map a cantilever's deflection • Extension - How can we use statistical analysis to determine the effectiveness of a given experimental setup?
PART 4 Instrumentation Design: Statistical Analysis with Instrumentation	• How can we use statistical analysis to determine the effectiveness of a given experimental setup? • How do statistical tests help scientists determine the validity of an experiment and its results?

Texas Essential Knowledge and Skills (TEKS)

This lesson was developed as cross-curricular, supporting Physics and Mathematics TEKS.

Part 1	Part 2	Part 3	Part 4	§112.39. Physics
				(2) Scientific processes. The student uses a systematic approach to answer scientific laboratory and field investigative questions. The student is expected to:
√	√	√	√	(D) design and implement investigative procedures, including making observations, asking well defined questions, formulating testable hypotheses, identifying variables, selecting appropriate equipment and technology, evaluating numerical answers for reasonableness, and identifying causes and effects of uncertainties in measured data;
	√	√	√	(E) demonstrate the use of course apparatus, equipment, techniques, and procedures, including multimeters (current, voltage, resistance), balances, batteries, dynamics demonstration equipment, collision apparatus, lab masses, magnets, plane mirrors, convex lenses, stopwatches, trajectory apparatus, graph paper, magnetic compasses, protractors, metric rulers, spring scales, thermometers, slinky springs, and/or other equipment and materials that will produce the same results;
	√	√	√	(F) use a wide variety of additional course apparatus, equipment, techniques, materials, and procedures as appropriate such as ripple tank with wave generator, wave motion rope, tuning forks, hand-held visual spectroscopes, discharge tubes with power supply (H, He, Ne, Ar), electromagnetic spectrum charts, laser pointers, micrometer, caliper, computer, data acquisition probes, scientific calculators, graphing technology, electrostatic kits, electroscope, inclined plane, optics bench, optics kit, polarized film, prisms, pulley with table clamp, motion detectors, photogates, friction blocks, ballistic carts or equivalent, resonance tube, stroboscope, resistors, copper wire, switches, iron filings, and/or other equipment and materials that will produce the same results;
	√	√	√	(G) make measurements with accuracy and precision and record data using scientific notation and International System (SI) units;
	√	√	√	(H) organize, evaluate, and make inferences from data, including the use of tables, charts, and graphs;
√	√	√	√	(I) communicate valid conclusions supported by the data through various methods such as lab reports, labeled drawings, graphic organizers, journals, summaries, oral reports, and technology-based reports; and
	√	√	√	(J) express relationships among physical variables quantitatively, including the use of graphs, charts, and equations.
				(3) Scientific processes. The student uses critical thinking, scientific reasoning, and problem solving to make informed decisions within and outside the classroom. The student is expected to:
√	√	√	√	(A) analyze, evaluate, and critique scientific explanations by using empirical evidence, logical reasoning, and experimental and observational testing, so as to encourage critical thinking by the student;
				(4) Science concepts. The student knows and applies the laws governing motion in a variety of situations. The student is expected to:
	√	√		(D) calculate the effect of forces on objects, including the law of inertia, the relationship between force and acceleration, and the nature of force pairs between objects using methods, including free body force diagrams.

Part 1	Part 2	Part 3	Part 4	§111.39. Algebra I
				(1) Mathematical process standards. The student uses mathematical processes to acquire and demonstrate mathematical understanding. The student is expected to:
	√	√	√	(B) use a problem-solving model that incorporates analyzing given information, formulating a plan or strategy, determining a solution, justifying the solution, and evaluating the problem-solving process and the reasonableness of the solution;
	√	√	√	(C) select tools, including real objects, manipulatives, paper and pencil, and technology as appropriate, and techniques, including mental math, estimation, and number sense as appropriate, to solve problems;
	√	√	√	(D) communicate mathematical ideas, reasoning, and their implications using multiple representations, including symbols, diagrams, graphs, and language as appropriate;
	√	√	√	(E) create and use representations to organize, record, and communicate mathematical ideas;
	√	√	√	(F) analyze mathematical relationships to connect and communicate mathematical ideas; and
	√	√	√	(G) display, explain, and justify mathematical ideas and arguments using precise mathematical language in written or oral communication.
				(2) Linear functions, equations, and inequalities. The student applies the mathematical process standards when using properties of linear functions to write and represent in multiple ways, with and without technology, linear equations, inequalities, and systems of equations. The student is expected to:
	√	√	√	(B) write linear equations in two variables in various forms, including $y = mx + b$, $Ax + By = C$, and $y - y1 = m(x - x1)$, given one point and the slope and given two points;
	√	√	√	(C) write linear equations in two variables given a table of values, a graph, and a verbal description;
				(3) Linear functions, equations, and inequalities. The student applies the mathematical process standards when using graphs of linear functions, key features, and related transformations to represent in multiple ways and solve, with and without technology, equations, inequalities, and systems of equations. The student is expected to:
	√	√	√	(A) determine the slope of a line given a table of values, a graph, two points on the line, and an equation written in various forms, including $y = mx + b$, $Ax + By = C$, and $y - y1 = m(x - x1)$;
	√	√	√	(C) graph linear functions on the coordinate plane and identify key features, including x-intercept, y-intercept, zeros, and slope, in mathematical and real-world problems;
				(4) Linear functions, equations, and inequalities. The student applies the mathematical process standards to formulate statistical relationships and evaluate their reasonableness based on real-world data. The student is expected to:
			√	(A) calculate, using technology, the correlation coefficient between two quantitative variables and interpret this quantity as a measure of the strength of the linear association;
	√	√	√	(C) write, with and without technology, linear functions that provide a reasonable fit to data to estimate solutions and make predictions for real-world problems.
	√	√	√	(F) analyze mathematical relationships to connect and communicate mathematical ideas; and
	√	√	√	(G) display, explain, and justify mathematical ideas and arguments using precise mathematical language in written or oral communication.

Part 1	Part 2	Part 3	Part 4	§111.4. Geometry	
				(1) Mathematical process standards. The student uses mathematical processes to acquire and demonstrate mathematical understanding. The student is expected to:	
√	√	√	√		(D) communicate mathematical ideas, reasoning, and their implications using multiple representations, including symbols, diagrams, graphs, and language as appropriate;
√	√	√	√		(E) create and use representations to organize, record, and communicate mathematical ideas;
√	√	√	√		(F) analyze mathematical relationships to connect and communicate mathematical ideas; and
√	√	√	√		(G) display, explain, and justify mathematical ideas and arguments using precise mathematical language in written or oral communication.
				(7) Similarity, proof, and trigonometry. The student uses the process skills in applying similarity to solve problems. The student is expected to:	
		√	√		(B) apply the Angle-Angle criterion to verify similar triangles and apply the proportionality of the corresponding sides to solve problems.
				(9) Similarity, proof, and trigonometry. The student uses the process skills to understand and apply relationships in right triangles. The student is expected to:	
		√	√		(A) determine the lengths of sides and measures of angles in a right triangle by applying the trigonometric ratios sine, cosine, and tangent to solve problems

<table>
<tr><th>Objective/s- Write objective/s
The student should be able to:</th><th>Assessment:
What will you accept as evidence of student progress toward your lesson objective?</th></tr>
<tr><td>PART 1
Identify the forces acting upon a cantilever.
Demonstrate and describe qualitatively how force causes deflection of a cantilever.
Describe qualitatively how a material's adhesive properties impact the force required to detach it from a surface.</td><td>Part 1
Students will articulate how the lab setup models the real-life scenario of AFMs and the mechanical force/action required to free the cantilever. Students will explain how the movement of their arm exerts a force on the model. Students will also be able to qualitatively describe and order the force required to disturb various tape samples and relate these forces to the cantilever’s deflection.
Formative Assessment: The teacher will formatively assess student understanding as they walk around and ask questions to students/groups as they are working through the activity or handout.</td></tr>
<tr><td>PART 2
Identify and illustrate the forces acting upon a mass suspended from a cantilever by drawing and labeling a free body diagram for the system in equilibrium.
Graphically represent the relationship between deflection and mass added to the free end of a cantilever.
Mathematically model the behavior of a cantilever system with an equation and graph, developing Hooke’s law and recognizing the spring constant.</td><td>PART 2
Students will be able to quantitatively describe how a cantilever’s deflection relates to the amount of force exerted with the use of Hooke’s law.
Students will calculate the spring constant for the given cantilever system.
Students will algebraically manipulate (rearrange) the equation for the spring constant.
Students should be able to draw a free body diagram for the mass suspended from a cantilever.
Formative Assessment will be happening as the teachers walk around and ask questions to students/groups as they are working through the activity or handout.</td></tr>
</table>

Objective/s- Write objective/s The student should be able to:	**Assessment:** What will you accept as evidence of student progress toward your lesson objective?
PART 3 ● Identify and illustrate the path and angle of the reflected incident light. ● Graphically represent the relationship between the change in the angle of the incident light and the mass added to the free end of a cantilever. ● Graphically represent the relationship between the change in the angle of the incident light and deflection when mass is added to the free end of a cantilever.	PART 3 ● Students will effectively articulate how instrumentation with angle of reflection and angle of incidence can be used to map surfaces with AFMs. ● Formative Assessment will be happening as the teachers walk around and ask questions to students/groups as they are working through activity or handout.
PART 4 ● Identify and illustrate the path and angle of the reflected incident light. ● Graphically represent the relationship between the change in the angle of the incident light and the mass added to the free end of a cantilever. ● Graphically represent the relationship between the change in the angle of the incident light and deflection when mass is added to the free end of a cantilever. ● Statistically analyze discrepancies between experimental values and theoretical values using a chi-squared test. ● Draw a conclusion about the effectiveness of this experiment with statistical tests.	PART 4 ● Students will be able to determine the effectiveness of this instrumentation through the use of statistical analysis (Pearson's Chi-Squared Test). ● Students will calculate the p-value for Pearson's Chi-Squared Test through the use of excel or other computer software and draw a conclusion based on that finding. ● Formative Assessment will be happening as the teachers walk around and ask questions to students/groups as they are working through activity or handout.

PART 1: Understanding the Impact of Force on Cantilevers

ENGAGEMENT

Estimated Time: 6 minutes

Overview of Activity: Students will be introduced to AFMs through a writing activity. In the process, the students will learn the components and significance of AFMs in universities and interdisciplinary research.

Resources Needed: whiteboard & dry erase markers or poster paper & markers to record student comments

Safety Considerations: None.

What the teacher is doing:	What the student does:	Possible questions to ask students and anticipated student responses:
The teacher prepares a large page or whiteboard to write students' responses. The teacher asks students, "What is the smallest you can write?" • Give the students 1-2 minutes to write and then compare student work. • Introduce AFMs as an instrument that can measure and image materials on the nanometer scale. • Introduce the main components of an AFM: probe (cantilever + scanning tip), position-sensitive photodiode, & laser • Share image of "IBM" written in atom • Share an image of the relative size of a nanometer (example graphic: https://introtonanotechnology.weebly.com/the-nanoscale.html) The teacher facilitates students' discussion and invites groups to share their answers.	The teacher prepares a large page or whiteboard to write students' responses. The students participate in writing activity and discussion. The teacher facilitates students' discussion and invites groups to share their answers. Students share their responses. If desired, or if prompting is needed, students can do this think-pair-share style: students think about the question independently, discuss possible answers with a partner, and then share with the class.	"What is the smallest you can write? What "font-size" would you call that?" • Allow students 1 or 2 minutes to work on this. • *2-point font* "Why is it important to have instruments that can look at small objects?" • *We can understand the fundamentals of our world.* • *Using this can further technology, making existing equipment more efficient.*

PART 1: Understanding the Impact of Force on Cantilevers

EXPLORATION

Estimated Time: 25 minutes

Overview of Activity: Students will qualitatively explore the cantilever's movement as forces act on the cantilever. Throughout the exploration, students will write their observations to discuss with group members and the class.

Resources Needed:

- Per group: meter stick, roll of painter's tape, roll of duct tape, roll of scotch tape, scissors
- Per student: "AFM Activity 1 Lab Sheet: Understanding Forces' Impact on Cantilevers" handout, writing utensils

Safety Considerations: Be mindful of your surroundings when using a meter stick to avoid collisions. Avoid putting excessive force on the meter stick, causing it to break. If the meter stick breaks, be careful of the sharp end and dispose of it immediately.

What the teacher is doing:	What the student does:	Possible questions to ask students and anticipated student response:
Throughout the activity, the teacher takes the role of facilitator and "lead-learner." Pass out materials to each student group or have a predetermined team equipment manager pick them up from a designated location. Pass out the "AFM Activity 1 Lab Sheet" handout (includes instructions for setup) to each student. After independently reading through the handout, have students discuss the activity with their group and develop a short list of what they know and wonder. Have them think through their questions and try to reason through them before sharing them with you. Doing so will identify student groups	In student groups of 3-4: Students read through the experimental setup and observations section of the "AFM Activity 1 Lab Sheet" handout. Students will discuss the activity and observation questions with their group, recording what they know and wonder about and discussing any potential questions or concerns. Students will follow the directions on the handout to set up the experiment before proceeding to conducting the experiment and recording their findings. Once completed, students will disassemble the experiment and	• On first look, what are some differences you notice between the tapes? ○ *the painter's tape is easier to tear* ○ *different colors* ○ *the packing tape is plastic* • What does it feel like to exert force on the measuring stick? ○ *the stick is pushing back* • What forces are acting on the cantilever while you are pushing up? ○ *Applied force from the hand pushing up.* ○ *Gravitational force acting down.* ○ *Force from the tape down.* For this question, it is important to note that the hand does not

uncertain of the directions and promote cooperation skills while encouraging autonomy.
 	
Note: It may be necessary to model how to attach the measuring sticks to the table's surface.
 	
As students work in their groups,
• Make sure each group has set up the experiment correctly.
• Ensure each student is participating.
• Rotate between groups and ask guiding questions to individual students within each group:
  ○ Goal: provide students time to process the different aspects of the system and how one may impact the other and assess student understanding as they work through the activity.
  ○ Use open-ended and guiding questions to encourage critical thinking while subsequently holding students accountable for their learning.
	return the materials to the proper location.	always exert a force on an object. For example, in a kinematic problem, once the object leaves the hand, no force is exerted. Making this clarification can help prevent misunderstanding of future concepts.
		
		• What changes do you notice in the stick as you exert a force upward on it? Can you be more specific?
		  ○ *it starts to bend or curve upward about halfway from where we lifted*
		
		• Where did you decide you would apply force to the measuring stick? Why?
		  ○ *The end to give the most leverage*
		  ○ *In the middle of the extended part bc it's easier to hold.*
		
		• What happens if you add more tape?
		  ○ *you have to lift more*
		  ○ *Multiple pieces are stronger than a single piece*

PART 1: Understanding the Impact of Force on Cantilevers

EXPLANATION

Estimated Time: 15 minutes

Overview of Activity: Students will qualitatively discuss the exploration activity, including how the setup models a real-world scenario, describe how a material's adhesive properties impact the force required to detach it from a surface and how force causes deflection of a cantilever as well as explain the impact of forces on the cantilever's deflection.

Resources Needed: whiteboard & dry erase markers or poster paper & markers to record student comments

Safety Considerations: None.

What the teacher is doing:	**What the student does:**	**Possible questions to ask students and anticipated student response:**

The teacher guides a whole-group discussion over the students' experiences during the activity and their observations.
 	
The teacher asks students to summarize the activity and their observations. The teacher acts as the facilitator and provides prompting, guiding questions, and open-ended questions.
 	
The teacher records student comments on the whiteboard or poster paper.
	Students follow the teacher's lead in a whole group discussion.
	
	Students discuss:
	• the relationship between the experiment's setup and how forces act upon the system.
	• how their interactions with the model impacted the system.
	
	Another option would be to have each group create a poster summarizing the experiment and the group's observations. Student groups would present their posters and answer guiding questions provided by the teacher.
		NOTE: For additional guiding questions, see the suggested questions in the exploration phase
		
		• Can someone summarize what the activity was modeling?
		  ○ *The force required to remove the meter stick must exceed the force exerted by the tape on the cantilever.*
		
		• Is the magnitude of the force required to detach the meter stick the same or different for the different tapes? Why might this be?
		  ○ *The packing tape was the hardest to detach and needed the most force. It's stickier than the others.*
		  ○ *You hardly needed any force to detach the scotch tape.*
		
		• How would you rank them? Did anyone get something different?
		  ○ *Listing them from least to greatest: x, y, z*

		○ *Listing them from greatest to least: z, y, x* ● Did you notice a difference in how easy it was to apply force with your arm in a particular direction or if you held them a certain way? If so, explain why you think that occurs. ○ *Yes, when I moved my arm like a bicep curl, it was easier than when I reached over the top and lifted my shoulders because that muscle is stronger.* ● What happens if you add more tape? ○ *You have to lift more.* ○ *Multiple pieces are stronger than a single piece.* ○ *The strength is the same - even though we increase the force, the pressure per square inch should be the same.* ● Is the amount of force required to detach the meter stick the same or different for the different tapes? Why? ○ *The packing tape was the hardest to detach and needed the most force. It's stickier than the others.* ○ *You hardly needed any force to detach the scotch tape.*

PART 1: Understanding the Impact of Force on Cantilevers

ELABORATION

Estimated Time: 15 minutes

Overview of Activity: Provides students an opportunity to apply or extend the new ideas and information on AFMs and deflection with force on a cantilever system.

Resources Needed: whiteboard & dry erase markers or poster paper and markers to record student comments

Safety Considerations: None.

What the teacher is doing:	What the student does:	Possible questions to ask students and anticipated student response:
The teacher facilitates the discussion by providing guiding questions geared to help students apply or expand upon the day's lessons over forces on cantilever systems. The teacher records student comments on the whiteboard or poster paper. 1. The teacher guides students to discuss the various forces that act upon the system and how to model the forces exerted on a biofilm while force is applied to a cantilever. The teacher guides students to create free body force diagrams of the system. 2. In the original activity, many of the variables have been specified for you, including the length of the cantilever, the types, width, and location of the tape, and the position you exert force. Consider what would happen if you	Students take part in active discussion and subsequent activity. If desired, or if prompting is needed, students can do this think-pair-share style: students think about the question independently, discuss possible answers with a partner, and then share with the class. 1. Students draw free body force diagrams depicting the lab activity. 2. Students replicate the experiment by changing the parameters of their choice.	*Questions will depend on the direction the elaboration phase takes. See Extension activity. Possible ideas:* 1. Free Body Force Diagrams ● Would it be possible to quantify the experiment we did today? ● Why would a scientist want to quantify the experiment? What kind of information would this provide? ● How can we visually model the forces that were exerted on the cantilever? ● What other forces act upon the system? 2. Suggestions for modifications ● Modify the adhesive ○ Test different types of adhesive (ex., CommandTM Strips, poster mounting putty, washi tape, Velcro®, etc.) ○ Increase or decrease the amount of tape/adhesive.

changed one or more of those parameters. *Some suggestions:* • *Propose three possible changes to the system to test. How do you think this would impact the system?* • *Hypothesize what will happen when force is exerted on the new system.*		○ Change the location of the tape/adhesive • Modify the cantilever ○ Increase or decrease the length of the cantilever • Modify the location of the force exerted on the system

PART 1: Understanding the Impact of Force on Cantilevers

EVALUATION

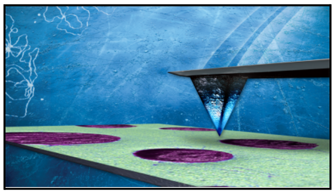
Estimated Time: Embedded throughout the lesson. Account for time required for pre-assessments and post-assessments (if necessary)

Overview of Activity: Formative and summative assessment of student understanding and effectiveness of the lesson.

Resources Needed: varies

Safety Considerations: None.

What the teacher is doing:	What the student does:	Possible questions to ask students and anticipated student response:
Throughout the lesson and activity, the teacher uses formative assessments to determine how much the students understand and if they are grasping the new concepts, as well as to evaluate the quality of the lesson. Formative assessment occurs during the learning process, provides an opportunity to identify the need for flexibility in instruction, identifies areas for improvement (both for student and for the lesson), and allows students a chance to implement feedback. Examples of formative assessment include hand signals, direct or indirect questioning, quizzes, observations, homework, and classwork. Summative assessment is completed at the end of the learning process and provides an evaluation of student concept knowledge. Summative assessment will often include evaluating the student work products, such as responses on the guided notes/handouts, posters, teacher-created exit slips, or unit tests.	Throughout the lesson, students work in groups to answer questions regarding the experiment and observations. Students will also answer questions independently when prompted by the teacher during the lesson phases or through teacher-prepared pre-assessments, post-assessments, or exit slips.	*See questions embedded in the sections above. Also, see accompanying Part 1 handout.*



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Atomic Force Microscopes (AFMs)

PART 1: Understanding How Forces Impact Cantilevers & Springs

Introduction

The **atomic-force microscope (AFM)** is a powerful tool that can image almost any surface, including polymers, ceramics, composites, glass, and biological samples. AFMs use a **cantilever** as part of the instrumentation design. A cantilever is a long projecting beam fixed at one end and can be conceptualized as a spring. If you have one end fixed and you displace the other free end up or down, the resulting force from the cantilever will look like a spring force. Using a sharp 10 to 20 nm diameter tip attached to a cantilever, the AFM takes advantage of the atomic forces between the probe and the sample's surface. As the tip of the AFM probe moves in response to tip-sample interactions, the cantilever beam experiences vertical **deflections.** Deflection is the displacement, or a shift, in the object's location from the original position due to the application of force. In an AFM, an optical system that includes focusing a laser beam with a photodiode measures this deflection. In the process, the AFM can measure and localize many forces, including adhesion, magnetic forces, and mechanical properties, to create a 3-D surface profile of the sample.

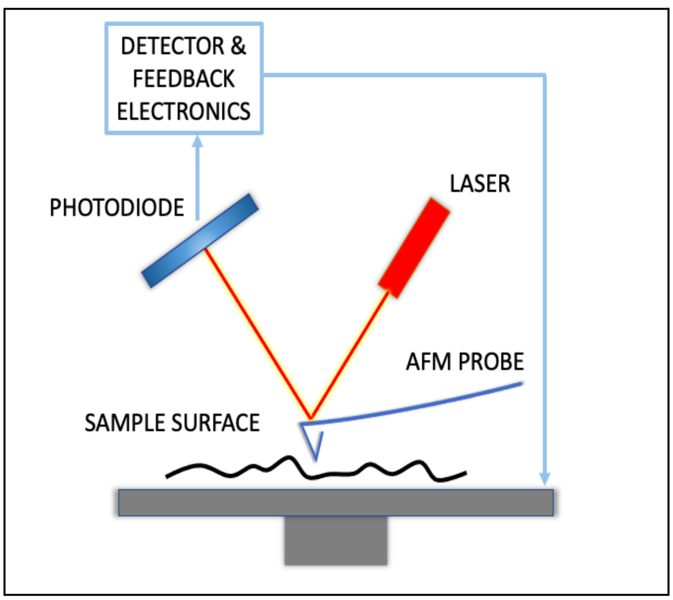

Figure 1: *Atomic force microscope (AFM) schematic.*

This activity will provide insight into how an AFM works by qualitatively investigating the impact of force applied to a cantilever. The same deflection-force relationship that occurs in cantilevers is also exhibited in springs.

In this lab, you will learn how to:

- identify the forces acting upon a cantilever.
- demonstrate and describe qualitatively how force causes deflection of a cantilever.
- describe qualitatively how a material's adhesive properties impact the force required to detach it from a surface.

Activity: Understanding How Force Impacts Cantilever & Springs

Safety Precautions:

- Be mindful of your surroundings when using a meter stick to avoid collisions.
- Avoid putting excessive force on the meter stick, causing it to break. If the meter stick breaks, be careful of the sharp end and dispose of it immediately.

For this activity, you will need the following:

- Wooden meter stick
- Roll of masking or painter's tape (2″ width; if 2″ tape is not available, double 1″ masking tape)
- Roll of packing tape (2″ width)
- Roll of duct tape (2″ width)
- Scissors
- Writing utensil

For this activity you will work *in teams of three or four*.

Activity Introduction

During this activity, you will be exerting force on a cantilever attached to a table with tape. Your cantilever will be a meter stick. Your team will conduct the experiment three times, using different types of tape for each attempt. Throughout the investigation, consider each trial independently, but also think about how the new trials compare to the previous ones.

Pre-Lab Questions

- First, carefully read the description and questions in the Procedure and Observation sections.
- Next, answer the pre-lab questions before starting the lab.

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1. What do you notice or wonder about the setup?

2. What forces are acting upon the system shown in Figure 2 (before attempting to lift the meter stick)? What forces are acting upon the system when you lift the meter stick?

3. What do you anticipate will happen to the meter stick when you apply force? What do you think will happen to the setup as a whole?

4. Do you anticipate all three tapes will hold the same? Do you think they will behave the same? Why or why not?

5. What are the intended takeaways from this activity?

Procedure

Step 1: Start with the masking tape. Cut three pieces of masking tape, each approximately 10 cm in length.

Step 2: With 70 cm of the meter stick extending past the edge of the table, use the three tape pieces to attach the meter stick to the table. Place the tape pieces from 0-5 cm, 13-18 cm, and 25-30 cm of the meter stick.

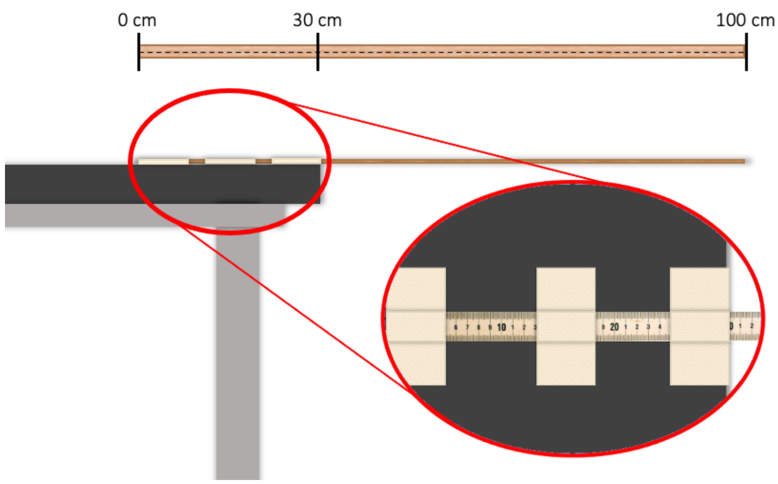

Figure 2: *Experimental setup with 2" masking tape.*

Step 3: With your hand centered around the 90 cm mark, gently lift the meter stick with constant force until the meter stick detaches from the table.

Step 4: Reaffix the tape and allow the next team member to try the activity. Repeat until each team member has participated in the activity. Record your observations in Table 1.

Step 5: Remove the masking tape and repeat the activity using the packing tape. Again, each team member should attempt the activity while the meter stick is affixed with packing tape. Record your individual observations in Table 1 after each team member has completed their turn.

Step 6: Remove the packing tape and repeat the activity using the duct tape. Again, each team member should attempt the activity while the meter stick is affixed with duct tape. Record your individual observations in Table 1 after each team member has completed their turn.

Observations

1. In Table 1 below, describe how you lifted the meter stick. Did you hold the meter stick from above and pull upward, or did you hold it from underneath and bring your forearms up (like a bicep curl)? Does how you hold and lift the meter stick impact the outcome?

Table 1: Qualitative Observations of Applied Force on a Cantilever

OBSERVATIONS	Masking Tape (or Painter's Tape)	Packing Tape	Duct Tape
	What does the process of lifting the meter stick feel like in your muscles?		

2. Describe changes to the meter stick and tape throughout the experiment.

3. Sketch what the system looked like right before the tape was pulled off the table.

4. Was it equally difficult to remove the meter stick when it was taped down with the different types of tape? Explain why or why not.

5. How does this activity better explain deflection associated with an applied force on a cantilever?

6. Based on your observations, describe qualitatively the force exerted by the different types of tape on the system. What does it imply to say they all exerted the same force on the system? Is this accurate?

Extension Activities

In the activity above, many of the variables have been specified for you, including the length of the cantilever, the types, width, and location of the tape, and the position you exert force. Consider what would happen if you changed one or more of those parameters.

- Purpose three possible changes to the system to test. How do you think this would impact the system?
- Hypothesize what will happen when force is exerted on the new system.
- Test your hypothesis and record your observations in Table 1.2.

EXTENSION	**Suggestions for modifications**

	• *Modify the adhesive*
	  ○ *Test different types of adhesive (ex., Command™ Strips, poster mounting putty, washi tape, Velcro®, etc.)*
	  ○ *Increase or decrease the amount of tape/adhesive*
	  ○ *Change the location of the tape/adhesive*
	• *Modify the cantilever*
	  ○ *Increase or decrease the length of the cantilever*
	• *Modify the location of the force exerted on the system*

Table 1.2: Extension of Qualitative Observations of Applied Force on a Cantilever

	Trial 1	**Trial 2**	**Trial 3**
Proposed Change			
Hypothesis			
Observations			
Did your observations support your hypothesis? Why or why not?			

Assessment

1. How is deflection related to force? Explain your thinking.

2. Describe the forces that act upon a cantilever.

3. In what way is the resulting change in the system of force exerted on a cantilever similar to changes that would result in a spring when force is exerted upon it?

4. How do the adhesive properties of a material impact the force required to detach it from a surface?