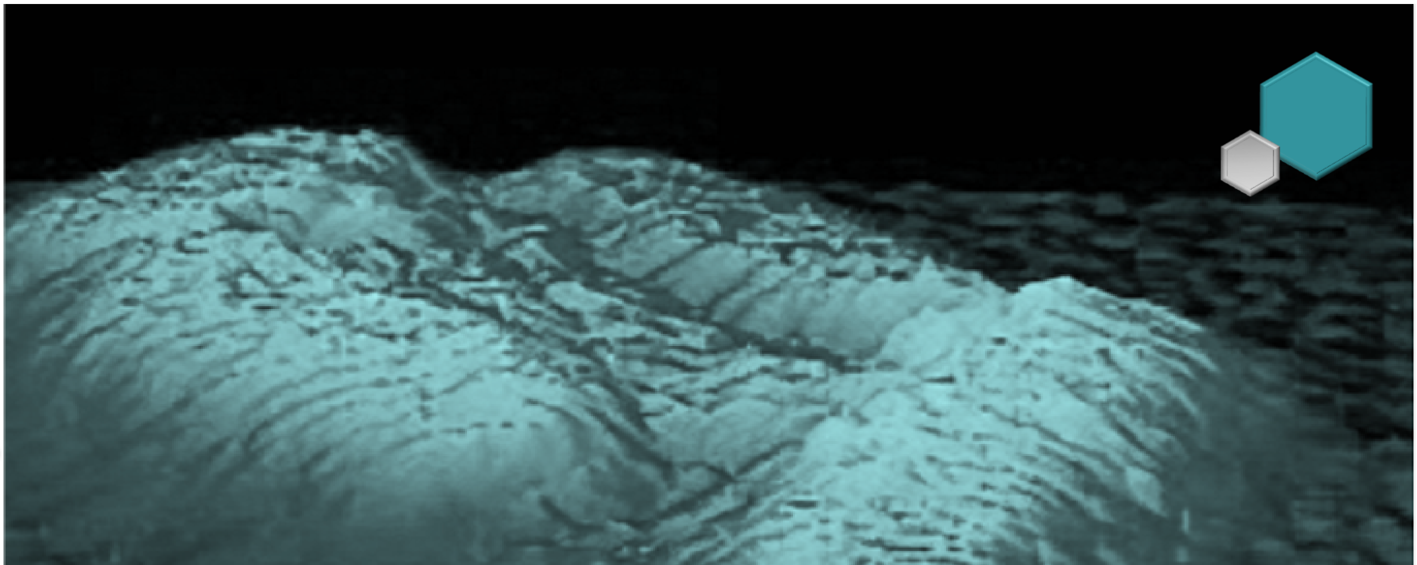
PHYSICS: Atomic Force Microscopes

How does an Atomic Force Microscope work?



PARTS 3: Instrument Design: Understanding How AFMs Use Optics & Reflected Light to Determine Sample Properties

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 3: Instrument Design: Understanding How AFMs Use Optics & Reflected Light to Determine Sample Properties	√	√

*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 1: Understanding How Forces Impact Cantilevers & Springs	√	√
PART 2: Hooke's Law: Calculating the Relationship Between Deflection & Applied Force in Cantilevers	√	√
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

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 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.	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.
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.	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.

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 3: Instrument Design: Understanding How AFMs Use Optics & Reflected Light to Determine Sample Properties

ENGAGEMENT

Estimated Time: 10 minutes

Overview of Activity: Students will discuss nanoscience – what it is, why it's important, and how AFMs play a role in it.

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 introduces nanoscience - what it is, why it's important, and how AFMs play a role. The teacher will then discuss the main mechanics of an AFM and how it is used to quantify substances on the nanoscale. The main point will be to connect optics in instrumentation as an introduction to the lab activity and make it relevant to how optics are used in the real world. Teacher shares ideas on nanoscale and nanotechnology. • https://www.science.org.au/curious/nanoscience#:~:text=Nanoscience%20has%20the%20potential%20to,from%20manufacturing%20to%20health%20care (There is a helpful graphic on this page that helps students better visualize what a nanometer is.) Note: students may struggle with visualizing a nanometer and may not have a good grasp of scientific	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.	Have you ever heard of a nanometer? What is it? • *A ninth of a meter* (incorrect assumption) • *$1x10^{-9}m$* Just how small do you think a nanometer is? What objects would be measured in nanometers? • *They are too small to see.* • *Size of a molecule* Why is it helpful to study substances on the nanoscale? • *To understand how something works* • *Understanding something at the nanoscale could help us lead to breakthroughs in manufacturing or health care.* Knowing what an AFM is capable of, in what ways can you think it could be used?

notation. This resource provides a good comparison: https://www.nano.gov/nanotech-101/what/nano-size#:~:text=A%20human%20hair%20is%20approximately,fingernail%20grows%20in%20one%20second “A nanoparticle to an ant, is the same ratio as an ant to a race track.” The teacher facilitates students' discussion and invites groups to share their answers.		• *characterizing bacteria and cells* • *analyzing DNA molecules* • *studying proteins in real-time* • *imaging molecules down to sub-atomic resolution.*

PART 3: Instrument Design: Understanding How AFMs Use Optics & Reflected Light to Determine Sample Properties

EXPLORATION

Estimated Time: 25 minutes

Overview of Activity: Students will explore angle of incidence and angle of reflection through instrumentation of a cantilever and laser system.

Resources Needed:

- Per group: 2 wooden meter sticks, 1 metric ruler, 1” x 1” mirror, 2 C-clamps, laser pointer (red or green), 1 ring-stands with clamps (one to hold the laser pointer and one to hold the meter stick), weights (ranging in mass: 0 g, 50g, 100 g, 150g, 200 g, 250g, 300 g), weight holder or string, two pieces of printer paper, tape, colored pencils & highlighters
- Per student: “AFM Activity 3 Lab Sheet – Incident Light” handout, writing utensils
- Note: You may also want to test the equipment prior to completing the activity with students to ensure you are not asking students to add more mass to the system than the meter stick can hold.

Safety Considerations:

- Mirrors are generally made of glass, so handle them carefully.
- Do not look directly into the laser; the light can damage your eye.
- Do not aim the laser at anyone’s face.
- Keep the laser turned off when not taking measurements.
- Be mindful of your surroundings when using a meter stick to avoid collisions.
- Avoid putting excessive force on the meter stick and breaking it. If the meter stick breaks, be careful of the sharp end and dispose of it immediately.
- Be cautious when putting weights on the meter stick. Heavy weights can cause injury when dropped. Avoid standing or putting your hands in locations in which weights could fall.
- Be cautious when using the clamps so as not to pinch fingers.

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 3 Lab Sheet – Calculating Hooke's Law” handout to each student.	In student groups of 3-4: Students read through the “Procedure” section of the “AFM Activity 3 Lab Sheet – Incident Light” handout. Students will discuss the activity and observation questions with their group, recording what they know and wonder about and	What are some of your controlled variables? • *Position of the laser (angle of the laser relative to the mirror)* • *Placement of mirror, masses, etc.* How does the horizontal displacement look? Does the trend match what we did last time?

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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 uncertain of the directions and promote cooperation skills while encouraging autonomy.
Note: It may be necessary to model how to set up the experiment.
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.

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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 return the materials to the proper location.

Leave one set up for students who want to do the extension activity.

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The horizontal displacement looks equally spaced out (linear). The trend matches the results from the last experiment.

Should the vertical deflection match the same trend? Why or why not?

The vertical deflection should match the linear trend from the last lesson since it follows Hooke’s law.

Would this setup work if the laser was angled? Why or why not?

The setup would work if the laser was angled, but you would need to measure the angle of the incident ray relative to the normal line of the mirror’s center each time.

Why would this be helpful in real life?

This would be helpful when designing buildings with a lot of exterior glass.
Measure small changes in research experiments.
Used as a tool in detecting changes for earthquakes.

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PART 3: Instrument Design: Understanding How AFMs Use Optics & Reflected Light to Determine Sample Properties

EXPLANATION

Estimated Time: 15 minutes

Overview of Activity: Students will mathematically model the behavior of a cantilever system with an equation and graph. Students will also relate the angle of incidence to the angle of reflection of vertical deflection.

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

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.
 	
The teacher allows students to present their ideas and findings to the class on the board/document camera.
• ask the class if they got the same/different answers.
	Students follow the teacher's lead in a whole group discussion.
	
	Students discuss:
	
	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.
		Did everyone get a linear trend?
		• *Yes, the relationship is the same as in the previous lesson.*
		• *No, my graph does not look linear.*
		  ○ *Ask what may have led to this (i.e., random and systematic errors or exceeding the elastic limit of the meterstick)*
		
		Does this trend still follow Hooke's law?
		• *Yes, it is a linear relationship.*
		
		How does the vertical deflection relate to the horizontal deflection?
		• *They are proportional.*
		  ○ *For an extension idea, calculate the scale factor for all the right triangles*.
		
		What is the relationship between the angle of incidence and angle of reflection? Is this relationship always true?

		• *They are equal, and it is always true.* How does the law of incidence and reflection connect to real-life situations? How does this relate to calculating Hooke's law and the usage of AFM? • *We can use the law of incidence and reflection to map rays of light. This will help in determining the deflection for small-scaled objects.*

PART 3: Instrument Design: Understanding How AFMs Use Optics & Reflected Light to Determine Sample Properties

ELABORATION

Estimated Time: 15 minutes

Overview of Activity: Provides students an opportunity to apply or extend the new ideas and information on the instrumentation of a cantilever system through statistical analysis.

Resources Needed: Dependent on activity.

Safety Considerations: Dependent on activity.

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 instrumentation with angle of incidence and angle of reflection. *See Part 4: Statistical Analysis with Instrumentation for ideas for Elaboration/extension.*	Students take part in active discussion and subsequent activity. If desired, or if prompting is needed, students can do this as a group.	Why should we consider the effectiveness of instrumentation? • *To ensure the data collection represents the experiment accurately.* Are there other ways to evaluate if this is a good model? • *We can use a t-test, look at linear regressions and evaluate the R^2 values.* What are some errors that you are consistently seeing? • *The laser was oscillating when marking down the point on the paper.* • *When measuring the angle, the string would not be perfectly straight (random error).*

PART 3: Instrument Design: Understanding How AFMs Use Optics & Reflected Light to Determine Sample Properties

EVALUATION

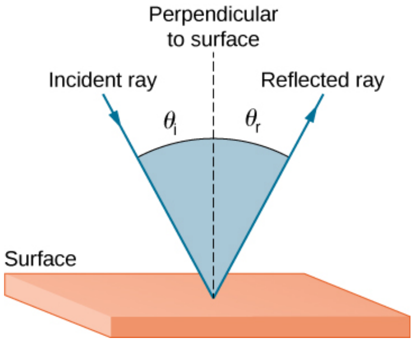
Estimated Time: Embedded throughout the lesson. Account for time required for pre-assessments, and post-assessments (if necessary)

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 3 handout.*



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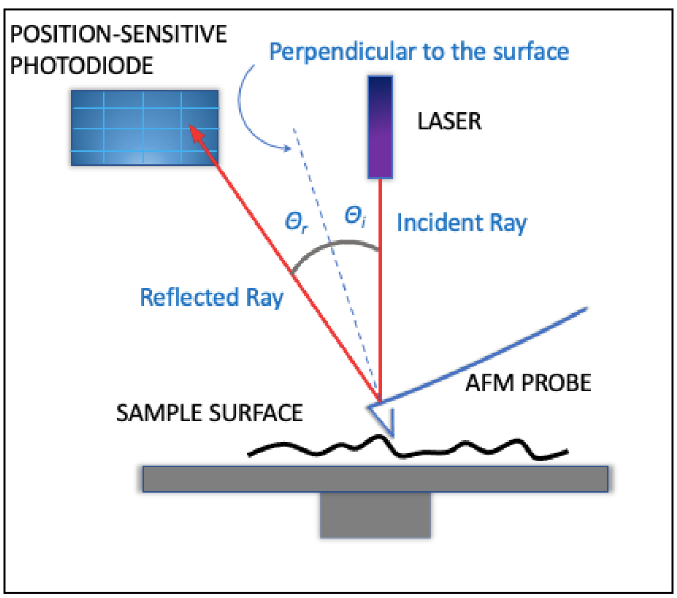
Atomic Force Microscopes (AFMs)

PART 3: Instrument Design: Understanding How AFMs Use Optics & Reflected Light to Determine Sample Properties

Introduction

Atomic force microscopes (AFMs) allow us to study samples at the nanoscale to measure and localize many forces, including adhesion, magnetic forces, and mechanical properties, to create a 3D surface profile of the sample. To do this, the AFM uses a cantilever system with a very sharp tip to traverse the surface of a material. Laser light is directed at a small mirror at the end of the cantilever. The **incident ray** then reflects onto a **position-sensitive photodiode (PSPD)**. As the cantilever deflects from forces exerted on the tip, slight changes occur in the **reflected ray**. The PSPD registers any changes in the position the reflected ray hits the photodiode. From this information and the known unchanging path of the incident ray from the laser, the **angle of incidence Θ_i** and **angle of reflection Θ_r**. can be calculated, and changes in these values are tracked. As the AFM passes over a raised surface, the PSPD records the change in the position of the reflected ray, and how that position is changing. From this information, we can calculate the change in the angle of incidence and the change in the cantilever deflection.



Figures 1: *Diagram of the optics system of an AFM.*

We can better understand how an AFM uses incident light to map properties of a sample's surface by adding mass to a cantilever system, shining a laser onto a mirror attached beneath the cantilever, and measuring the position of the reflected ray. As the cantilever tracks the surface of the sample, the cantilever deflects. This results in changes to the angle of incidence for the laser light shining onto the mirror – and, therefore, the angle of reflection. In turn, the position of where the reflected light hits the photodiode will change as the cantilever deflects under different loads.

In this lab, you will learn how to:

- identify and illustrate the path and angle of the reflected and incident rays.
- 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.

Activity: Calculating the Relationship Between Deflection & Applied Force in Cantilevers

Safety Precautions:

- Mirrors are generally made of glass, so handle them carefully.
- Do not look directly into the laser; the light can damage your eye.
- Do not aim the laser at anyone's face.
- Keep the laser turned off when not taking measurements.
- Be mindful of your surroundings when using a meter stick to avoid collisions.
- Avoid putting excessive force on the meter stick and breaking it. If the meter stick breaks, be careful of the sharp end and dispose of it immediately.
- Be cautious when putting masses on the meter stick. Heavy masses can cause injury when dropped. Avoid standing or putting your hands where the masses could fall.
- Be cautious when using the clamps so as not to pinch fingers.

For this activity, you will need the following:

- 2 wooden meter sticks
- 1 metric ruler
- 1" x 1" mirror
- 2 C-clamps
- laser pointer (red or green)
- ring-stand with 2 clamps (to hold the laser pointer and one of the meter sticks).
- weights (ranging in mass: 0 g, 50g, 100 g, 150g, 200 g, 250g, 300 g)
- weight holder or string
- two pieces of printer paper
- tape
- colored pencils & highlighters
- writing utensil

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

Activity Introduction

During this activity, you will use mass to apply force on the free end of a cantilever attached to a table with a fixed clamp. Your cantilever will be a meter stick with a mirror attached to the underside of the free end. You will set up the laser pointer to shine vertically upward to the mirror. Your team will modify the system five times, using different masses for each attempt. Throughout the investigation, consider each trial independently and how the new trials compare to the previous ones.

Pre-Lab Questions

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

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

2. Consider the setup before adding mass. What forces are acting on the cantilever? What forces are acting on the mass? Sketch and label the system. Use a different colored pencil or marker to indicate the direction of the various forces acting upon the system.

3. On the same diagram, draw what you anticipate will happen to the slope of the mirror when you apply force to the free end of the meter stick? Is there a limit to how you think the mirror will change? Explain your thinking.

4. Considering the lab setup and your previous experience with cantilever systems.
    a. How much deflection do you anticipate will occur with 100 g of added mass?

    b. What slope would you anticipate the mirror to be with this added weight relative to the horizontal axis? Sketch your prediction below.

    c. In the sketch above, use different colored pencils to draw the laser hitting the mirror. Use an additional color to sketch a dashed line indicating the direction of the line perpendicular to the mirror at the point the incident ray hits it.

    d. In the sketch above, continue the path of the incident ray to show your prediction for the path of the reflected ray. Where do you anticipate it will hit the ground? In your image, label the angle of incidence θ_i and the angle of the reflected ray θ_r .

5. Label your sketch with the vertical height component y_f of the cantilever and the horizontal distance of the reflected beam x_f. Letting $\alpha = \theta_r + \theta_i = 2\theta_i$, use trig functions to write an equation representing the relationship between x_f, y_f, and α. Rewrite the equation in terms of θ_i.

6. Do you predict any correlation between the variables x_f, y_f, θ_i, and the added mass? What relationship do you hypothesize exists between the variables and the added mass? Explain your thinking.

7. What are the intended takeaways from this activity?

Procedure

Step 1: Experimental Setup

Cantilever: Using the C-clamps, attach the meter stick horizontally to a table or desk surface with 70 cm of the meter stick hanging over the edge of the surface, as shown in Figure 2. Attach the mirror to the free end of the meter stick with 5 cm of free space at the end. Tie a length of string to the meter stick's free end. You can secure the string by wrapping it several times around the end of the meter stick and tapping it.

Laser: Attach the laser pointer to the ring stand with a clamp with the ray points vertically upward. *Use caution not to shine the laser at anyone or to look at it.* Place the ring stand directly under the mirror. Tape two pieces of paper together on the floor with the edge of one piece under the ring stand. You will record the position of the reflected beam on the paper as the lab progresses.

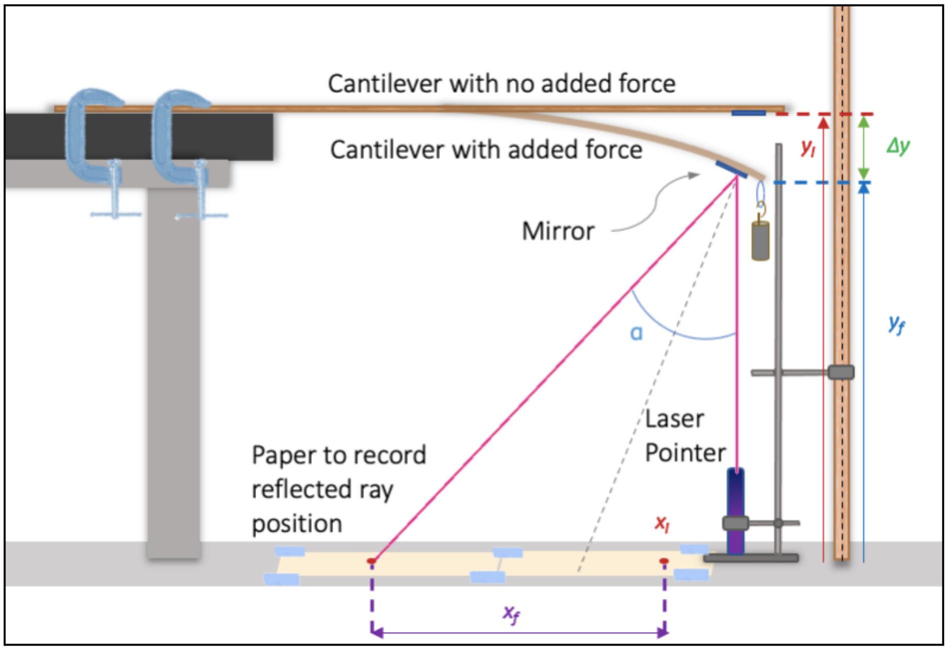

Figure 2: *Experimental setup*

Step 2: Take initial measurements
Cantilever height: Attach the second meter stick to the ring stand (perpendicular to the floor with the 0 cm at the floor.) Place the ring stand near the free end of the cantilever. Measure the height of the free end of the meter stick in centimeters to the closest millimeter. Record the initial height value in Table 1 as y_i (corresponding to 0 g of added mass).

Reflected light: With the laser pointer turned on, carefully mark where the reflected beam hits the paper. Label this point x_i. We will measure the distance the reflected beam hits the floor from this position as mass is added to the cantilever.

Step 3: Exert force on the cantilever & record new height
Attach the 50 g mass to the string and measure the height of the free end of the meter stick, measuring upward from the floor. Record the mass (in grams) and corresponding final height y_f of the end of the meter stick in Table 1.

Step 4: Record the location of reflected light
Mark the location of the reflected ray on the paper. Measure the horizontal distance of the new reflected ray from the initial position x_i to the nearest millimeter and record it in centimeters in Table 1.

Step 4: Repeat Steps 3 and 4 using 100g, 150g, 200g, 250g, and 300g.

Data, Observations, & Analysis

1. Sketch the cantilever set up with 100g of mass impacting the system. Discuss how your prediction from the pre-lab questions resembles the current setup with 100g of added mass. Are they different? How so? Explain your thinking.

2. Sketch the cantilever set up with 300g of mass impacting the system. Qualitatively compare the slope of the mirror in the two scenarios.

3. As you work through the lab, for each trial:

    a. Record the mass *m* and the resulting height of the cantilever x_i in Table 1. Calculate the deflection Δy ($\Delta y = y_i - y_f$).

    b. Record the horizontal distance of the reflected ray relative to the initial position x_i.

    c. Calculate the ratio of the vertical position to the horizontal position using x_i / y_i.

4. Using your trig equation from pre-lab question 5, calculate θ_i for each added mass. Record these values in Table 1 in degrees.

Table 1: Data Collection & Analysis

Mass of Attached Weight, *m* (g)	**Vertical Height, y_f (cm)**	**Vertical Deflection, Δy (cm)**	**Horizontal Position of the Reflected Ray, x_f (cm)***	**Ratio of Horizontal to Vertical Position, $\frac{x_f}{y_f}$**	**Angle of Incidence, θ_i (degrees)**
0	y_i =		x_i = 0	0	
50					
100					
150					
200					
250					
300					

**For m= 0 g, $y_i = y_f$. All other values of y_f are measured as the distance from y_i. Similarly, For m= 0 g, $x_i = x_f$. All other values of x_f are measured as the distance from x_i.*

5. On the provided graph (Figure 3), label the horizontal axis as “mass (m)” and the vertical axis as “Angle of Incidence θ_i (degrees).” Plot the angle of incidence as a function of added mass.

Relationship Between Angle of Incidence and Added Mass in a Cantilever

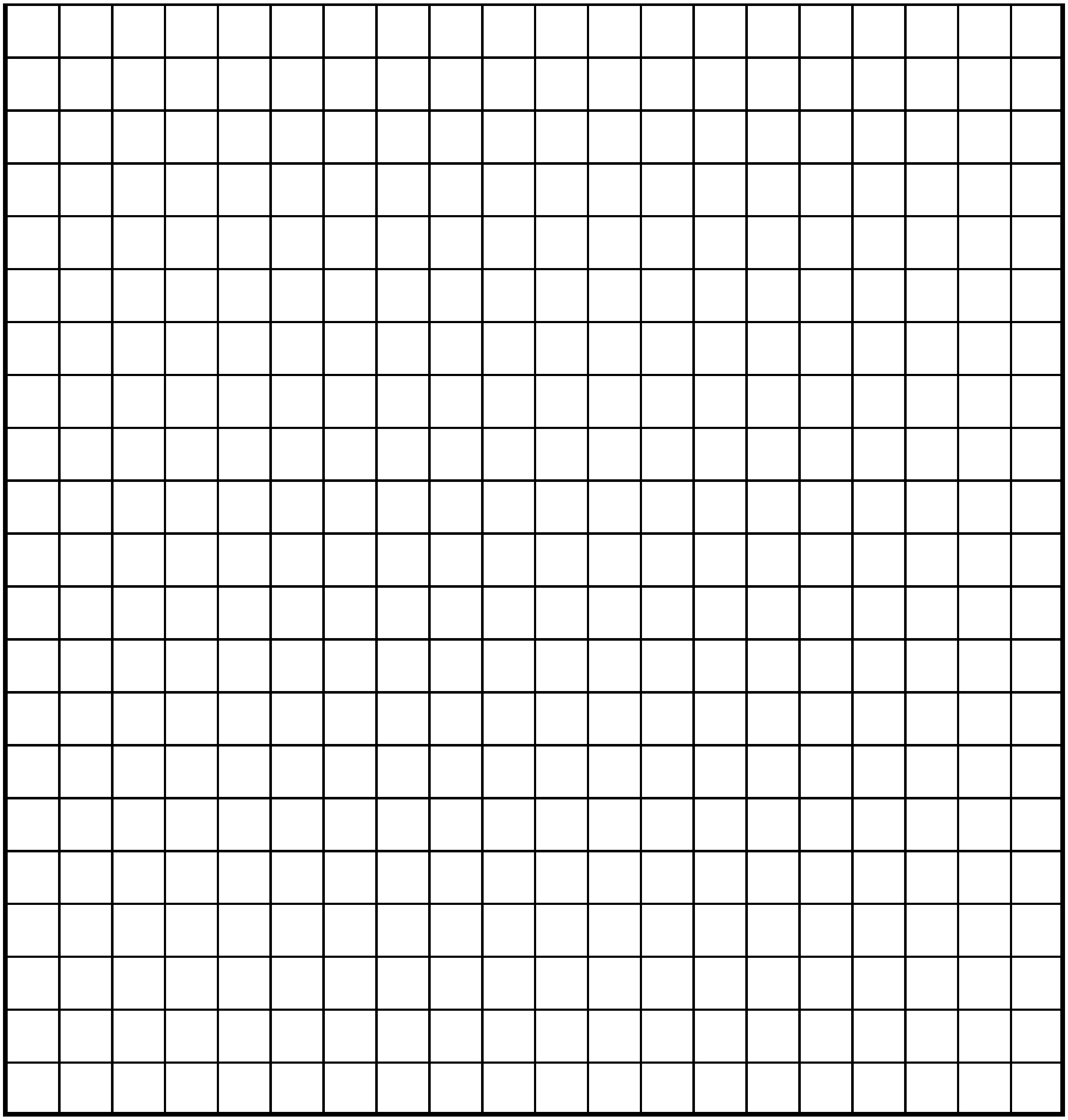

Figure 3. *Angle of Incidence versus Added Mass.*

6. Draw a line of best fit through the data points. What type of relationship best describes the graph you drew? What does the slope of the line of best fit represent? Describe the change in the angle of incidence as a function of added mass. Does this align with your trig equation from question 5 in the pre-lab? Why or why not?

7. On the provided graph (Figure 4), label the horizontal axis as "Angle of Incidence θ_i (degrees)" and the vertical axis as "Vertical Deflection Δy (cm)." Plot the vertical deflection as a function of the angle of incidence.

Relationship Between Deflection and Angle of Incidence in a Cantilever

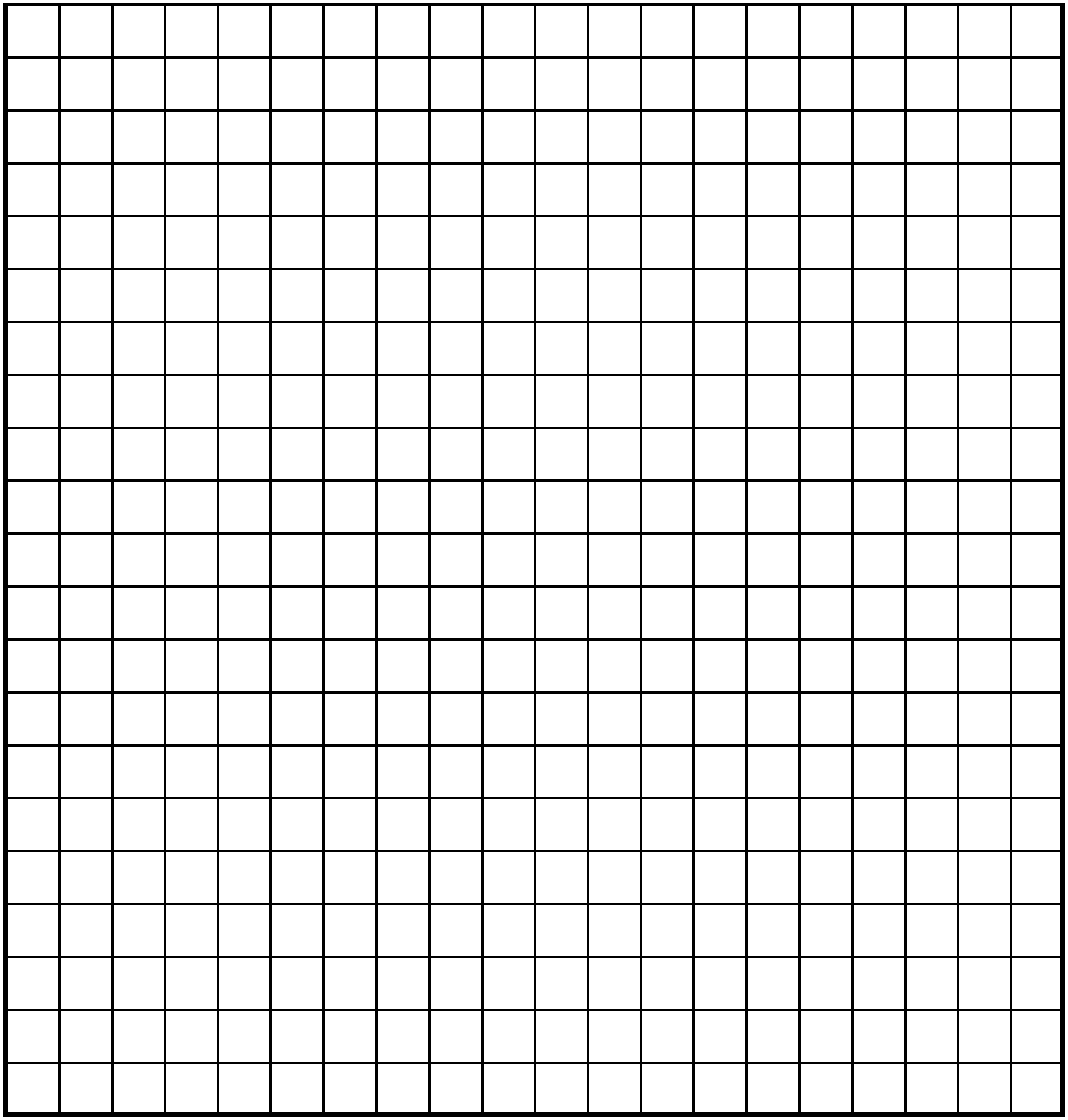

Figure 4. *Angle of Incidence versus Vertical Deflection.*

Assessment

1. Create a generalized formula that relates the angle of incidence and the deflection for the cantilever system in this investigation. Is this formula valid for all situations? Why or why not?

2. As the angle of incidence increases for a ray incident on a reflecting surface, what happens to the reflected angle? What must occur with a cantilever for the angle of incidence to increase?

3. What sources of error might there be with the experimental setup and instrumentation? Explain your thinking.

4. How does the law of incidence and reflection connect to real-life situations? Think back to the previous lessons. How does this relate to calculating Hooke's law and the usage of AFM?