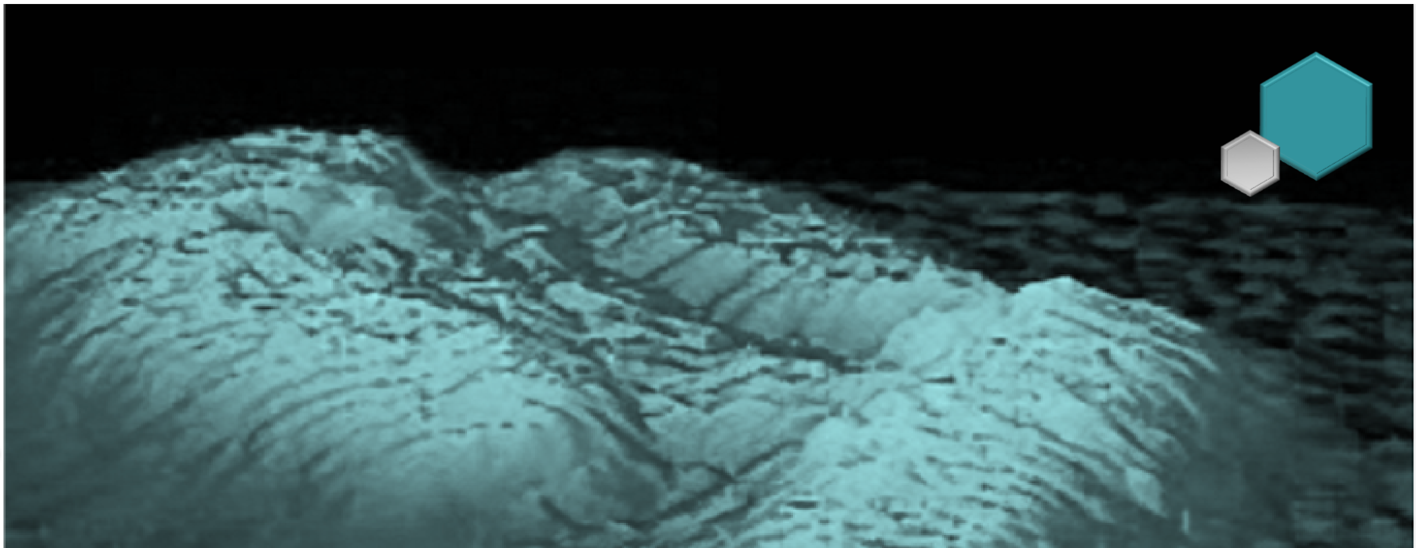
# PHYSICS: Atomic Force Microscopes

How does an Atomic Force Microscope work?



## PARTS 1-4:

- 1: Understanding How Forces Impact Cantilevers & Springs
- 2: Hooke's Law: Calculating the Relationship Between Deflection & Applied Force in Cantilevers
- 3: Instrument Design: Understanding How AFMs Use Optics & Reflected Light to Determine Sample Properties
- 4: Instrument Design: Statistical Analysis with Instrumentation

*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** | √ | √ |
| **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** | √ | √ |

*Activity lab sheets can be found in the Appendix of this document.

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?

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|---|---|
| **PART 1** Understanding How Forces Impact Cantilevers & Springs | • How do Atomic Force Microscopes use forces to map surfaces?<br>• 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?<br>• 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<br>• 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?<br>• 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 |

# LESSON PLAN: Atomic Force Microscopes

<table>
<tr><th>Objective/s- Write objective/s<br>The student should be able to:</th><th>Assessment:<br>What will you accept as evidence of student progress toward your lesson objective?</th></tr>
<tr><td>PART 1<ul><li>Identify the forces acting upon a cantilever.</li><li>Demonstrate and describe qualitatively how force causes deflection of a cantilever.</li><li>Describe qualitatively how a material's adhesive properties impact the force required to detach it from a surface.</li></ul></td><td>Part 1<ul><li>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.</li><li>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.</li></ul></td></tr>
<tr><td>PART 2<ul><li>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.</li><li>Graphically represent the relationship between deflection and mass added to the free end of a cantilever.</li><li>Mathematically model the behavior of a cantilever system with an equation and graph, developing Hooke’s law and recognizing the spring constant.</li></ul></td><td>PART 2<ul><li>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.</li><li>Students will calculate the spring constant for the given cantilever system.</li><li>Students will algebraically manipulate (rearrange) the equation for the spring constant.</li><li>Students should be able to draw a free body diagram for the mass suspended from a cantilever.</li><li>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.</li></ul></td></tr>
</table>

<table>
<tr><th>Objective/s- Write objective/s<br>The student should be able to:</th><th>Assessment:<br>What will you accept as evidence of student progress toward your lesson objective?</th></tr>
<tr><td>PART 3<ul><li>Identify and illustrate the path and angle of the reflected incident light.</li><li>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.</li><li>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.</li></ul></td><td>PART 3<ul><li>Students will effectively articulate how instrumentation with angle of reflection and angle of incidence can be used to map surfaces with AFMs.</li><li>Formative Assessment will be happening as the teachers walk around and ask questions to students/groups as they are working through activity or handout.</li></ul></td></tr>
<tr><td>PART 4<ul><li>Identify and illustrate the path and angle of the reflected incident light.</li><li>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.</li><li>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.</li><li>Statistically analyze discrepancies between experimental values and theoretical values using a chi-squared test.</li><li>Draw a conclusion about the effectiveness of this experiment with statistical tests.</li></ul></td><td>PART 4<ul><li>Students will be able to determine the effectiveness of this instrumentation through the use of statistical analysis (Pearson’s Chi-Squared Test).</li><li>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.</li><li>Formative Assessment will be happening as the teachers walk around and ask questions to students/groups as they are working through activity or handout.</li></ul></td></tr>
</table>

## 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.<br><br>The teacher asks students, “What is the smallest you can write?”<br>• Give the students 1-2 minutes to write and then compare student work.<br>• Introduce AFMs as an instrument that can measure and image materials on the nanometer scale.<br>• Introduce the main components of an AFM: probe (cantilever + scanning tip), position-sensitive photodiode, & laser<br>• Share image of “IBM” written in atom<br>• Share an image of the relative size of a nanometer (example graphic: https://introtonanotechnology.weebly.com/the-nanoscale.html)<br><br>The teacher facilitates students' discussion and invites groups to share their answers. | The teacher prepares a large page or whiteboard to write students' responses.<br><br>The students participate in writing activity and discussion.<br><br>The teacher facilitates students' discussion and invites groups to share their answers.<br><br>Students share their responses.<br><br>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?”<br>• Allow students 1 or 2 minutes to work on this.<br>• *2-point font*<br><br>“Why is it important to have instruments that can look at small objects?”<br>• *We can understand the fundamentals of our world.*<br>• *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."<br><br>Pass out materials to each student group or have a predetermined team equipment manager pick them up from a designated location.<br><br>Pass out the "AFM Activity 1 Lab Sheet" handout (includes instructions for setup) to each student.<br><br>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:<br><br>Students read through the experimental setup and observations section of the "AFM Activity 1 Lab Sheet" handout.<br><br>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.<br><br>Students will follow the directions on the handout to set up the experiment before proceeding to conducting the experiment and recording their findings.<br><br>Once completed, students will disassemble the experiment and | • On first look, what are some differences you notice between the tapes?<br>  ○ *the painter's tape is easier to tear*<br>  ○ *different colors*<br>  ○ *the packing tape is plastic*<br><br>• What does it feel like to exert force on the measuring stick?<br>  ○ *the stick is pushing back*<br><br>• What forces are acting on the cantilever while you are pushing up?<br>  ○ *Applied force from the hand pushing up.*<br>  ○ *Gravitational force acting down.*<br>  ○ *Force from the tape down.*<br>For this question, it is important to note that the hand does not |

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| uncertain of the directions and promote cooperation skills while encouraging autonomy.<br><br>Note: It may be necessary to model how to attach the measuring sticks to the table's surface.<br><br>As students work in their groups,<br>● Make sure each group has set up the experiment correctly.<br>● Ensure each student is participating.<br>● Rotate between groups and ask guiding questions to individual students within each group:<br>○ 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.<br>○ 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.<br><br>● What changes do you notice in the stick as you exert a force upward on it? Can you be more specific?<br>○ *it starts to bend or curve upward about halfway from where we lifted*<br><br>● Where did you decide you would apply force to the measuring stick? Why?<br>○ *The end to give the most leverage*<br>○ *In the middle of the extended part bc it's easier to hold.*<br><br>● What happens if you add more tape?<br>○ *you have to lift more*<br>○ *Multiple pieces are stronger than a single piece* |

# LESSON PLAN: Atomic Force Microscopes

## 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.<br><br>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.<br><br>The teacher records student comments on the white board or poster paper. | Students follow the teacher's lead in a whole group discussion.<br><br>Students discuss:<br>• the relationship between the experiment's setup and how forces act upon the system.<br>• how their interactions with the model impacted the system.<br><br>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*<br><br>• Can someone summarize what the activity was modeling?<br>  ○ *The force required to remove the meter stick must exceed the force exerted by the tape on the cantilever.*<br><br>• Is the magnitude of the force required to detach the meter stick the same or different for the different tapes? Why might this be?<br>  ○ *The packing tape was the hardest to detach and needed the most force. It's stickier than the others.*<br>  ○ *You hardly needed any force to detach the scotch tape.*<br><br>• How would you rank them? Did anyone get something different?<br>  ○ *Listing them from least to greatest: x, y, z* |

| | | |
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| | | ○ *Listing them from greatest to least: z, y, x*<br><br>● 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.<br>○ *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.*<br><br>● What happens if you add more tape?<br>○ *You have to lift more.*<br>○ *Multiple pieces are stronger than a single piece.*<br>○ *The strength is the same - even though we increase the force, the pressure per square inch should be the same.*<br><br>● Is the amount of force required to detach the meter stick the same or different for the different tapes? Why?<br>○ *The packing tape was the hardest to detach and needed the most force. It's stickier than the others.*<br>○ *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.<br><br>The teacher records student comments on the white board or poster paper.<br><br>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.<br><br>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.<br><br>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.<br><br>1. Students draw free body force diagrams depicting the lab activity.<br><br>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:*<br><br>1. Free Body Force Diagrams<br>● Would it be possible to quantify the experiment we did today?<br>● Why would a scientist want to quantify the experiment? What kind of information would this provide?<br>● How can we visually model the forces that were exerted on the cantilever?<br>● What other forces act upon the system?<br><br>2. Suggestions for modifications<br>● Modify the adhesive<br>○ Test different types of adhesive (ex., CommandTM Strips, poster mounting putty, washi tape, Velcro®, etc.)<br>○ Increase or decrease the amount of tape/adhesive. |

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

## PART 2: Hooke's Law: Calculating the Relationship Between Deflection & Applied Force in Cantilevers

### ENGAGEMENT

**Estimated Time:** 10 minutes

**Overview of Activity:** Students will be introduced to deflection and will relate it to an everyday activity. In the process, the students will connect the deflection of a cantilever to how an AFM functions to quantify characteristics of a sample.

**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 starts the lesson by asking students about their favorite summertime activities. The teacher then asks specifically about swimming and diving. Show a video on diving. After students have a chance to respond, relate the diving board to a cantilever. The more force the diver puts on the cantilever (diving board), the further it deflects. Mention how this is today's experiment with a meter stick as a cantilever and how this relates to AFMs; further discuss the relation to Hooke's law.<br><br>The teacher introduces the idea of Atomic Force Microscopes (AFM) and how the deflection of the cantilever can be represented by Hooke's law.<br><br>The teacher instructs students to do the pre-lab questions independently | Students share their responses.<br><br>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. | How many of you like swimming?<br>(This can also be related to the Olympic Diving if it is a competition year.)<br><br>Have any of you been diving?<br><br>What do you know about the mechanics of a diving board?<br>• *They bend when you jump on them.*<br><br>How do you think understanding the mechanics of a diving board would help scientists develop equipment?<br>• *Some equipment might bend like a diving board does?*<br><br>Have you ever heard of Hooke's Law? What do you know about it?<br>• *Never heard of it.*<br>• *Has to do with spring.* |

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| for 5 minutes, then they can discuss with their groups.<br><br>The teacher prepares a large page or whiteboard to write students' responses.<br><br>The teacher facilitates students' discussion and invites groups to share their answers. | | |

# PART 2: Hooke's Law: Calculating the Relationship Between Deflection & Applied Force in Cantilevers

## EXPLORATION

**Estimated Time:** 25 minutes

**Overview of Activity:** Students will explore Hooke's law through experimentation and graphing the relationship of force as a function of displacement. In the process, students will quantitatively evaluate the forces within the system and calculate the spring constant for their cantilever.

**Resources Needed:**

- Per group: 2 wooden meter sticks, 2 C-clamps, masses ranging in 0 g, 50g, 100 g, 150g, 200 g, 250g, 300 g, mass holder or string, tape
- Per student: "AFM Activity 2 Lab Sheet – Calculating Hooke's Law" 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:** 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."<br><br>Explain instructions and expectations to students. Students will begin the activity portion of the lesson by reading through the entire handout.<br><br>Pass out materials to each student group or have a predetermined team equipment manager pick them up from a designated location.<br><br>Pass out the "AFM Activity 2 Lab Sheet – Calculating Hooke's Law" handout to each student. | In student groups of 3-4:<br><br>Students read through the "Procedure" section of the "AFM Activity 2 Lab Sheet – Calculating Hooke's Law" handout.<br><br>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.<br><br>Students will follow the directions on the handout to set up the experiment before | What do you notice about the meter stick without any mass attached?<br>• *The meter stick is sagging down.*<br>• *The meter stick is drooping.*<br><br>How could having a bent meter stick initially affect your data?<br>• *It could make the initial data point inaccurate.*<br><br>As you are adding mass, what does your new height look like? Is it constantly changing?<br>• *The new height is getting smaller.* |

| | | |
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| After students read through the handout, reiterate instructions and have students discuss the activity with their group and develop a short list of what they know and wonder. Have the students 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.<br><br>Note: It may be necessary to model how to set up the experiment before passing out materials.<br><br>As students work in their groups,<br>● Make sure each group has set up the experiment correctly.<br>● Ensure each student is participating.<br>● Rotate between groups and ask guiding questions to individual students within each group:<br>○ 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.<br>○ Use open-ended and guiding questions to encourage critical thinking while subsequently holding students accountable for their learning. | proceeding to conduct the experiment and recording their findings.<br><br>Once completed, students will disassemble the experiment and return the materials to the proper location. | When you take off the mass, what happens to the meterstick? Why?<br>● *The meter stick bounces back up because the system wants to go back to equilibrium.*<br><br>How much mass do you think we can add before the cantilever breaks?<br>● *1000 grams*<br><br>What would your data look like if you were to add mass until the cantilever breaks?<br>● *The force versus displacement would start out as a linear relationship, but would start looking like a nonlinear graph with more added mass.* |

## PART 2: Hooke's Law: Calculating the Relationship Between Deflection & Applied Force in Cantilevers

<table>
<tr><td colspan="3">EXPLANATION<br>Estimated Time: 15 minutes<br>Overview of Activity: Students will mathematically model the behavior of a cantilever system with an equation and graph, developing Hooke's law and recognizing the spring constant.</td></tr>
<tr><td colspan="3">Resources Needed: handout, document camera.<br>Safety Considerations: None.</td></tr>
<tr><td>What the teacher is doing:</td><td>What the student does:</td><td>Possible questions to ask students and anticipated student response:</td></tr>
<tr><td>The teacher guides a whole-group discussion over the students' experiences during the activity and their observations.<br><br>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.<br><br>The teacher records student comments on the whiteboard or poster paper.<br><br>The teacher allows students to present their ideas and findings to the class on the board/document camera.<br>• Take this opportunity to ask the class if they got the same/different answers. This provides a chance for further</td><td>Students follow the teacher's lead in a whole group discussion.<br><br>Students discuss:<br>• The relationship between the experiment's setup and how it models Hooke's law.<br>• The relationship between applied force and displacement.<br><br>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.<br>• Could also do this in a jigsaw or gallery walk, which allows the students to provide anonymous feedback.</td><td>NOTE: For additional guiding questions, see the suggested questions in the exploration phase<br><br>What is the overall relationship between the force and deflection?<br>• There is a linear relationship between the force and deflection.<br><br>Why is it negatively linear?<br>• The displacement $\Delta x = x_i - x_f$, but if we were to write it as the traditional $\Delta x = x_f - x_i$, the negative would come out.<br>• As the force increases, the free end (height) of the cantilever is getting smaller.<br><br>Do all the points go through the line of best fit? Why or why not might this be?<br>• Not all the points go through the line of best fit. This could be due to random error (from measurement taking) or systematic error (the meterstick already sagging).</td></tr>
</table>

| | | |
|---|---|---|
| discussion and includes all of the class. | | What could we do differently in our experimental set up that could help remedy this?<br>• *Ensure the cantilever is perfectly horizontal with 0g added mass.*<br>• *Use more precise measuring tools.* |

## PART 2: Hooke's Law: Calculating the Relationship Between Deflection & Applied Force in Cantilevers

### ELABORATION

**Estimated Time:** 15 minutes

**Overview of Activity:** Provides students an opportunity to apply or extend the new ideas and information on the exploration of Hooke's law through 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 cantilever systems and Hooke's law.<br><br>The teacher records student comments on the whiteboard or poster paper.<br><br>The teacher asks students to consider how you could quantify adhesion bond strength.<br><br>The teacher guides students to discuss the various forces that act upon the system and how the cantilever system models Hooke's law. | Students take part in active discussion and subsequent activity.<br><br>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.<br><br>Students draw free body force diagrams depicting the lab activity. | *Questions will depend on the direction the elaboration phase takes. See Extension activity. Possible ideas:*<br><br>Is there a point where Hooke's law would fail? Why might this be?<br>• *There is not a point where Hooke's law would fail since it's a linear equation. (This is incorrect)*<br>• *Hooke's law will fail if the spring or cantilever is loose or overstretched. When taking data with flawed equipment, we will see that it does not follow Hooke's law.*<br><br>If a group got a curved line, this could mean that the meter stick was bent beyond its normal range. In that case, Hooke's law would fail.<br><br>Compare spring contents with other groups and materials. |

## PART 2: Hooke's Law: Calculating the Relationship Between Deflection & Applied Force in 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.<br><br>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.<br><br>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.<br><br>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.* |

## 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.<br>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.<br><br>Teacher shares ideas on nanoscale and nanotechnology.<br>• [https://www.science.org.au/curious/nanoscience#:~:text=Nanoscience%20has%20the%20potential%20to,from%20manufacturing%20to%20health%20care](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.)<br><br>Note: students may struggle with visualizing a nanometer and may not have a good grasp of scientific | Students share their responses.<br><br>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?<br>• *A ninth of a meter* (incorrect assumption)<br>• $1x10^{-9}m$<br><br>Just how small do you think a nanometer is? What objects would be measured in nanometers?<br>• *They are too small to see.*<br>• *Size of a molecule*<br><br>Why is it helpful to study substances on the nanoscale?<br>• *To understand how something works*<br>• *Understanding something at the nanoscale could help us lead to breakthroughs in manufacturing or health care.*<br><br>Knowing what an AFM is capable of, in what ways can you think it could be used? |

| | | |
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| notation. This resource provides a good comparison:<br><br>https://www.nano.gov/nanotech-101/what/nano-size#:~:text=A%20human%20hair%20is%20approximately,fingernail%20grows%20in%20one%20second<br><br>“A nanoparticle to an ant, is the same ratio as an ant to a race track.”<br><br>The teacher facilitates students' discussion and invites groups to share their answers. | | • *characterizing bacteria and cells*<br>• *analyzing DNA molecules*<br>• *studying proteins in real-time*<br>• *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.”<br><br>Pass out materials to each student group or have a predetermined team equipment manager pick them up from a designated location.<br><br>Pass out the “AFM Activity 3 Lab Sheet – Calculating Hooke's Law” handout to each student. | In student groups of 3-4:<br><br>Students read through the “Procedure” section of the “AFM Activity 3 Lab Sheet – Incident Light” handout.<br><br>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?<br>• *Position of the laser (angle of the laser relative to the mirror)*<br>• *Placement of mirror, masses, etc.*<br><br>How does the horizontal displacement look? Does the trend match what we did last time? |

| | | |
|---|---|---|
| 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.<br><br>Note: It may be necessary to model how to set up the experiment.<br><br>As students work in their groups,<br>• Make sure each group has set up the experiment correctly.<br>• Ensure each student is participating.<br>• Rotate between groups and ask guiding questions to individual students within each group:<br>  ○ 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.<br>  ○ Use open-ended and guiding questions to encourage critical thinking while subsequently holding students accountable for their learning. | discussing any potential questions or concerns.<br><br>Students will follow the directions on the handout to set up the experiment before proceeding to conducting the experiment and recording their findings.<br><br>Once completed, students will disassemble the experiment and return the materials to the proper location.<br>• *Leave one set up for students who want to do the extension activity.* | • *The horizontal displacement looks equally spaced out (linear). The trend matches the results from the last experiment.*<br><br>Should the vertical deflection match the same trend? Why or why not?<br>• *The vertical deflection should match the linear trend from the last lesson since it follows Hooke's law.*<br><br>Would this setup work if the laser was angled? Why or why not?<br>• *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.*<br><br>Why would this be helpful in real life?<br>• *This would be helpful when designing buildings with a lot of exterior glass.*<br>• *Measure small changes in research experiments.*<br>• *Used as a tool in detecting changes for earthquakes.* |

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

| | | |
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| | | <ul><li>*They are equal, and it is always true.*</li></ul>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?<ul><li>*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.*</li></ul> |

## 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.<br><br>*See Part 4: Statistical Analysis with Instrumentation for ideas for Elaboration/extension.* | Students take part in active discussion and subsequent activity.<br><br>If desired, or if prompting is needed, students can do this as a group. | Why should we consider the effectiveness of instrumentation?<br>• *To ensure the data collection represents the experiment accurately.*<br><br>Are there other ways to evaluate if this is a good model?<br>• *We can use a t-test, look at linear regressions and evaluate the $R^2$ values.*<br><br>What are some errors that you are consistently seeing?<br>• *The laser was oscillating when marking down the point on the paper.*<br>• *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.<br><br>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.<br><br>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.<br><br>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.* |

# LESSON PLAN: Atomic Force Microscopes

## PART 4: Instrumentation Design: Statistical Analysis with Instrumentation

<table>
<tr><td colspan="3">ENGAGEMENT<br>Estimated Time: 10 minutes<br>Overview of Activity:</td></tr>
<tr><td colspan="3">Resources Needed: whiteboard & dry erase markers or poster paper & markers to record student comments<br>Safety Considerations: None.</td></tr>
<tr><td>What the teacher is doing:</td><td>What the student does:</td><td>Possible questions to ask students and anticipated student responses:</td></tr>
<tr><td>The teacher introduces nanoscience - what it is, why it’s important, and how AFMs play a role.<br>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 the use of optics in instrumentation as an introduction to the lab activity and make it relevant to how optics are used in the real world.<br><br>Teacher shares ideas on nanoscale and nanotechnology.<ul><li>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.)</li></ul>Note: students may struggle with visualizing a nanometer and may not have a good grasp of scientific</td><td>Students share their responses.<br><br>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.</td><td>Have you ever heard of a nanometer? What is it?<ul><li>A ninth of a meter (incorrect assumption)</li><li>$1x10^{-9}m$</li></ul>Just how small do you think a nanometer is? What objects would be measured in nanometers?<ul><li>They are too small to see.</li><li>Size of a molecule</li></ul>Why is it helpful to study substances on the nanoscale?<ul><li>To understand how something works</li><li>Understanding something at the nanoscale could help us lead to breakthroughs in manufacturing or health care.</li></ul>Knowing what an AFM is capable of, in what ways can you think it could be used?</td></tr>
</table>

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

# PART 4: Instrumentation Design: Statistical Analysis with Instrumentation

Note: Part 4 of this series provides an alternate approach to exploring optic use within an AFM. While it can stand alone, it could also be used as an extension of 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:**

- 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, Protractor, laptop or calculator (to do the $\chi^2$ test and look up the $\chi^2$ table for p-values).
- 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."<br><br>Pass out materials to each student group or have a predetermined team equipment manager pick them up from a designated location.<br><br>Pass out the "AFM Activity 4 Lab Sheet – Statistical Analysis of Incident Light" handout to each student.<br><br>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.<br><br>Note: It may be necessary to model how to set up the experiment.<br><br>As students work in their groups,<br>• Make sure each group has set up the experiment correctly.<br>• Ensure each student is participating.<br>• Rotate between groups and ask guiding questions to | In student groups of 3-4:<br><br>Students read through the "Procedure" section of the "AFM Activity 4 Lab Sheet – Statistical Analysis of Incident Light" handout.<br><br>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.<br><br>Students will follow the directions on the handout to set up the experiment before proceeding to conducting the experiment and recording their findings.<br><br>Once completed, students will disassemble the experiment and return the materials to the proper location. | What are some of your controlled variables?<br>• *Position of the laser (angle of the laser relative to the mirror)*<br>• *Placement of mirror, masses, etc.*<br><br>How does the horizontal displacement look? Does the trend match what we did last time?<br>• *The horizontal displacement looks equally spaced out (linear). The trend matches results from the last experiment.*<br><br>Should the vertical deflection match the same trend? Why or why not?<br>• *The vertical deflection should match the linear trend from the last lesson since it follows Hooke's law.*<br><br>Would this setup work if the laser was angled? Why or why not?<br>• *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.* |

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| individual students within each group:<br>◦ 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.<br>◦ Use open-ended and guiding questions to encourage critical thinking while subsequently holding students accountable for their learning. | | How do the angles you are measuring differ between masses?<br>• *Theoretically, the angle will get larger, but due to the instrumentation, the change in angle will not be very big.*<br><br>Does the vertical deflection you calculated with the measured angles make sense?<br>• *The vertical deflections do not make sense. They are not following the linear trend.*<br><br>How does your p-value compare to the significance level, and what does this mean?<br>• *The p-value is less than the significance level; therefore, we* ***can reject*** *the null hypothesis.*<br>• *The p-value is greater than the significance level; therefore, we* ***cannot reject*** *the null hypothesis.*<br>• Note: it is important to mention that not rejecting the null hypothesis does not imply that the null hypothesis is **true**. |

## PART 4: Instrumentation Design: Statistical Analysis with Instrumentation

### 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 statistically analyze the significance of the instrumentation with Pearson's Chi-Squared Test.

**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.<br><br>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.<br><br>The teacher records student comments on the whiteboard or poster paper. | Students follow the teacher's lead in a whole group discussion.<br><br>Students discuss:<br><br>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. | Why did our angles not match the expected values?<br>● *Random error: each will be slightly off since we did each measurement by hand.*<br>● *Systematic error: There could be an offset with the way the string is placed.*<br><br>What was the conclusion from the statistical analysis?<br>● *Failed to reject the null hypothesis.*<br>● *Rejected the null hypothesis.*<br><br>How could using statistical tests help determine the effectiveness of an experiment?<br>● We can determine if there is statistical significance. |

## PART 4: Instrumentation Design: Statistical Analysis with Instrumentation

| **ELABORATION**<br>**Estimated Time:** 15 minutes<br>**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.<br>**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. | Students take part in active discussion and subsequent activity.<br><br>If desired, or if prompting is needed, students can do this as a group. | Why should we consider the effectiveness of instrumentation?<br>• *To ensure the data collection represents the experiment accurately.*<br><br>Are there other ways to evaluate if this is a good model?<br>• *We can use a t-test, look at linear regressions and evaluate the* $R^2$ *values.*<br><br>What are some ethical problems that might arise with statistical analysis?<br>• *People can change the conclusion by changing the significance level.*<br>• *People can also alter the p-value by the way they analyze their data.* |

## PART 4: Instrumentation Design: Statistical Analysis with Instrumentation

### EVALUATION

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

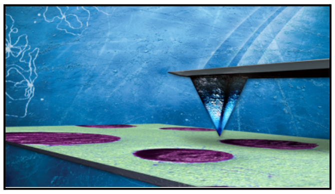
**Overview of Activity:** Formative and summative assessment of student understanding and effectiveness of the lesson.

**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.<br><br>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.<br><br>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.<br><br>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.* |

# APPENDIX



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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.

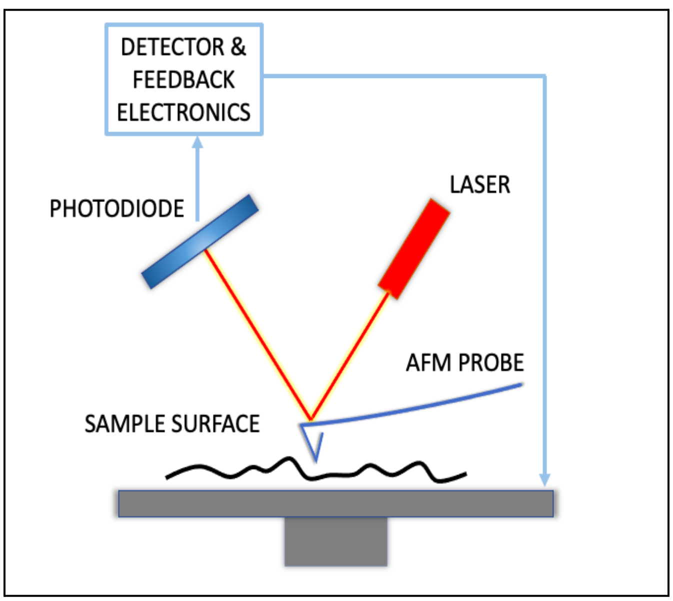



***Figure 1:*** *Atomic force microscope (AFM) schematic.*

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.

---

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 take-aways 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.

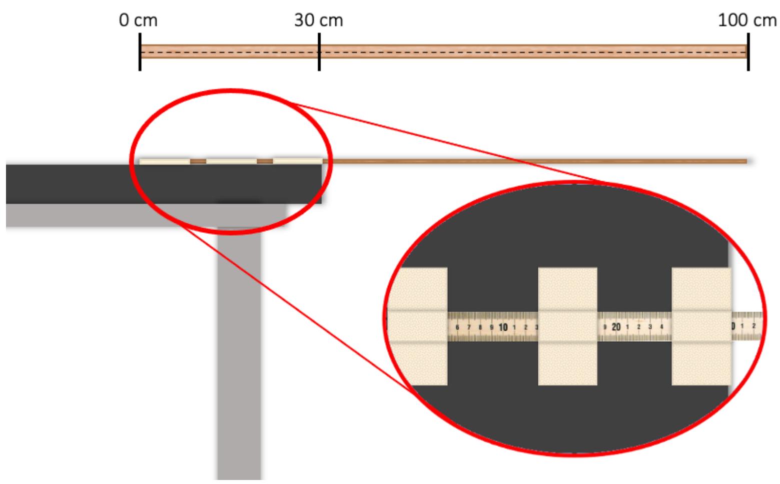



***Figure 2:*** *Experimental setup with 2" masking tape.*

**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?** | | | |

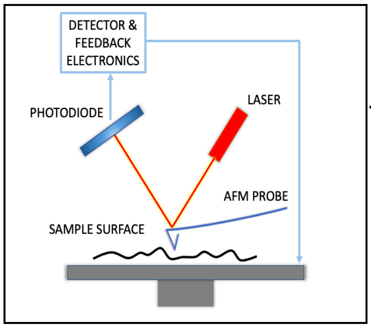
## Assessment

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?



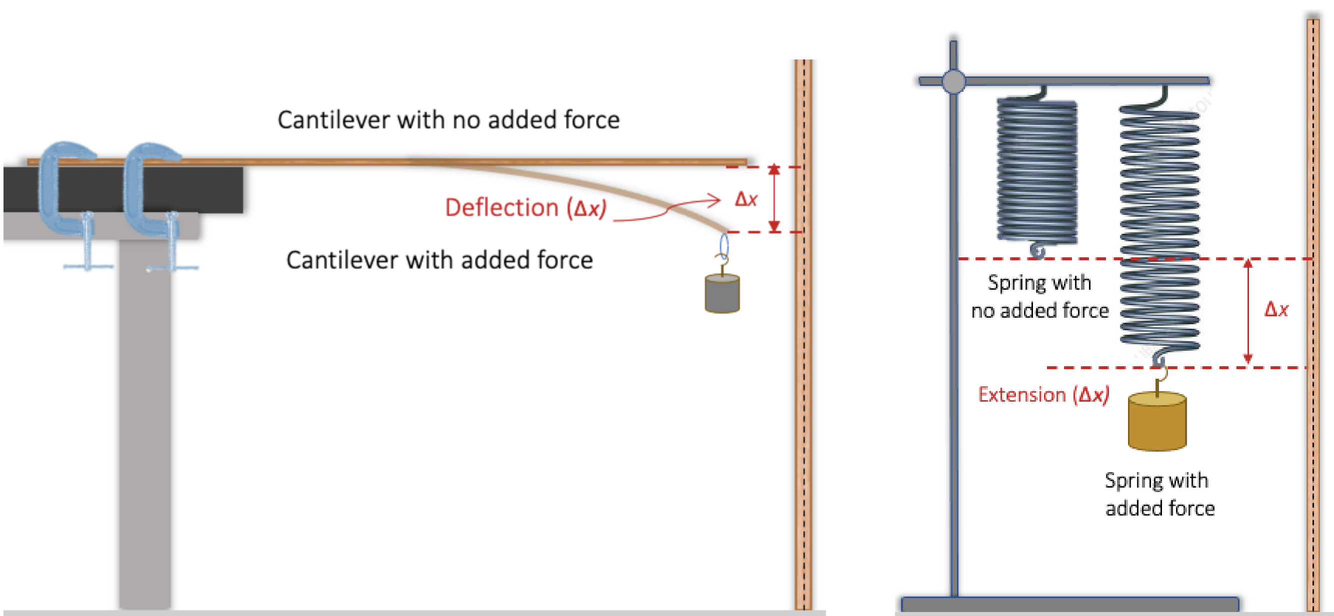

# Atomic Force Microscopes (AFMs)

## PART 2: Hooke's Law: Calculating the Relationship Between Deflection & Applied Force in Cantilevers

### Introduction

**Atomic force microscopes (AFM)** use a cantilever to measure and localize many forces, including adhesion, magnetic forces, and mechanical properties, to create a 3D surface profile of the sample. Much like a spring, the magnitude of the cantilever's deflection, or displacement, depends on the beam's material and the force applied to it.

With cantilevers, **Hooke's law** mathematically relates the **deflection** ($\Delta x$) of a cantilever when weight is added to the **force** (F) exerted by the cantilever to keep the system in equilibrium. Similarly, with springs, Hooke's law relates the force applied to an unstretched spring and the amount it stretches. Although some materials may seem similar, each system exhibits Hooke's law differently due to an inherent characteristic called the **spring constant** (k). Figures 1a & 1b show Hooke's law for cantilever and spring in action, respectively.




***Figures 1a & 1b:*** *Displacement of a cantilever and spring due to application of mass on the system.*

We can validate Hooke's law by adding mass to a cantilever system and measuring the resulting deflection. This activity will provide insight into how an AFM works by quantitatively investigating the impact of force applied to a cantilever and deriving Hooke's law for a given system.

**In this lab, you will learn how to:**

- 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.

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

**Safety Precautions:**

- 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.

**For this activity, you will need the following:**

- 2 wooden meter sticks
- 2 C-clamps
- weights (ranging in mass: 0 g, 50g, 100 g, 150g, 200 g, 250g, 300 g)
- weight holder or string
- tape
- writing utensil

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

## Activity Introduction

During this activity, you will apply force on the free end of a cantilever attached to a table with a fixed clamp. Your cantilever will be a meter stick. Your team will conduct the experiment 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.

---

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

2. What forces are acting upon the cantilever shown in Figure 2 (before adding mass to the meter stick)? What forces are acting upon the mass when added to the free end of the meter stick?

3. What do you anticipate will happen to the meter stick when you apply force to the free end of the meter stick? Explain your thinking.

4. In this lab, you will derive Hooke's law – the mathematical relationship between force exerted upon a cantilever or spring and the resulting displacement. What mathematical relationship do you hypothesize would best describe this relationship (ex., proportional, inversely related, quadratic)? Explain your thinking.

5. What do you hypothesize will happen to the cantilever when we remove the mass from the system? Explain your thinking.

6. What are the intended takeaways from this activity?

## Procedure

**Step 1:** 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.

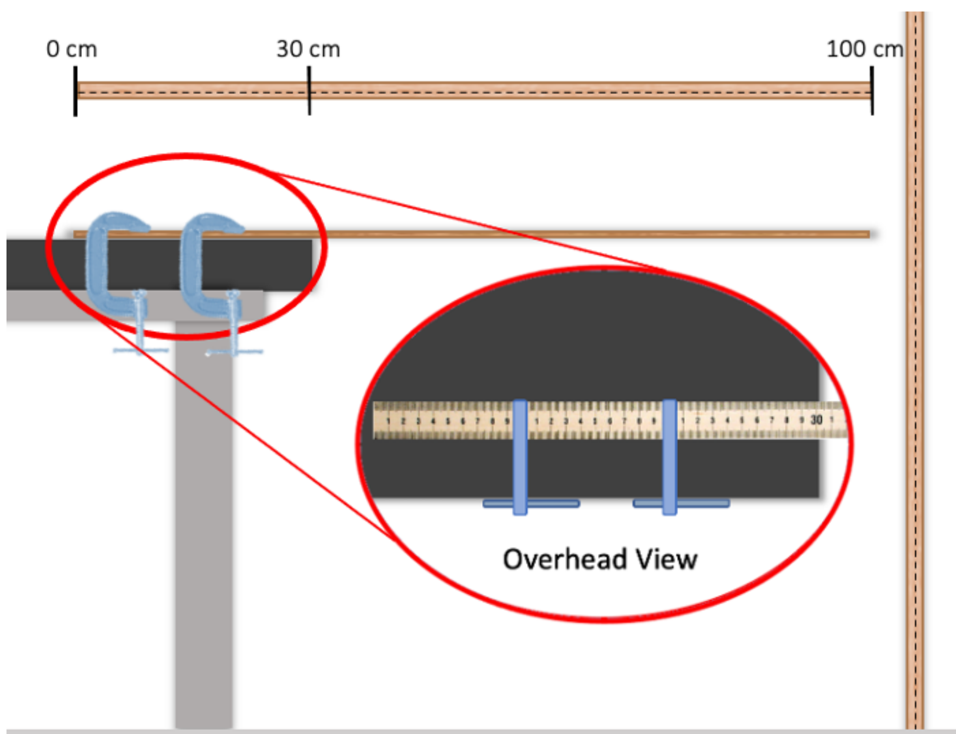



***Figure 2:*** *Experimental setup*

**Step 2:** Place the second meter stick near the cantilever (perpendicular to the floor with the 0 cm at the floor.) 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 $x_i$ (corresponding to 0 g of added mass).

**Step 3:** 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.

**Step 4:** Attach the 100 g weight to the string and measure the height of the free end of the meter stick, measuring upward from the floor. Record the mass of the added weight (in grams) and corresponding final height $x_f$ of the end of the meter stick in Table 1.

**Step 5:** Repeat Step 4 using 100 g, 150 g, 200 g, 250 g, and 300 g.

## Data, Observations, & Analysis

7. Draw and label two free body diagrams of the mass: one while the mass is not attached to the cantilever and the second with the mass suspended from the cantilever. Be sure to include the force of weight.

8. As you work through the lab, record the mass of the attached weights and the resulting height of the cantilever in Table 1. Calculate the vertical deflection by subtracting the new height of the cantilever's end after each trial from the initial height ($\Delta x = x_i - x_f$.)

**Table 1:** Data Collection

| Mass of Attached Weight, *m* (g) | Vertical Height, $x_f$ (cm) | Vertical Deflection, $\Delta x = x_i - x_f$ (cm)* |
|---|---|---|
| 0 | $x_i$ = | 0 |
| 100 | | |
| 200 | | |
| 300 | | |
| 400 | | |
| 500 | | |

**For m= 0 g, $x_i$=$x_f$ ,therefore, Δx = 0 cm.*

9. Calculate the force (F) exerted on the cantilever by the added masses for each trial. Record the values in Table 2. Recall that force is equal to mass times acceleration (F = m·a), where a is the acceleration due to gravity (a = 9.81 $m/s^2$ ). Copy the vertical deflection from Table 1 to Table 2, **converting centimeters to meters**. Note that the mass units have been converted to kg to report force in terms of Newtons (N = kg·$m/s^2$).

**Table 2:** Data Processing

| Mass of Attached Weight, m (kg) | Force Exerted by Cantilever on the weight, F = m·a (N) | Vertical Deflection, $\Delta x = x_i - x_f$ (m)* |
|---|---|---|
| 0.000 | 0 | 0 |
| 0.100 | | |
| 0.200 | | |
| 0.300 | | |
| 0.400 | | |
| 0.500 | | |

**Report Δx in meters.*

10. On the provided graph (Figure 3), label the x-axis as “Vertical Deflection (Δx)” and the y-axis as “Force (F).” Plot the deflection as a function of added mass. Refer to the deflection distance using the symbol Δx.

## Modeling Hooke’s Law

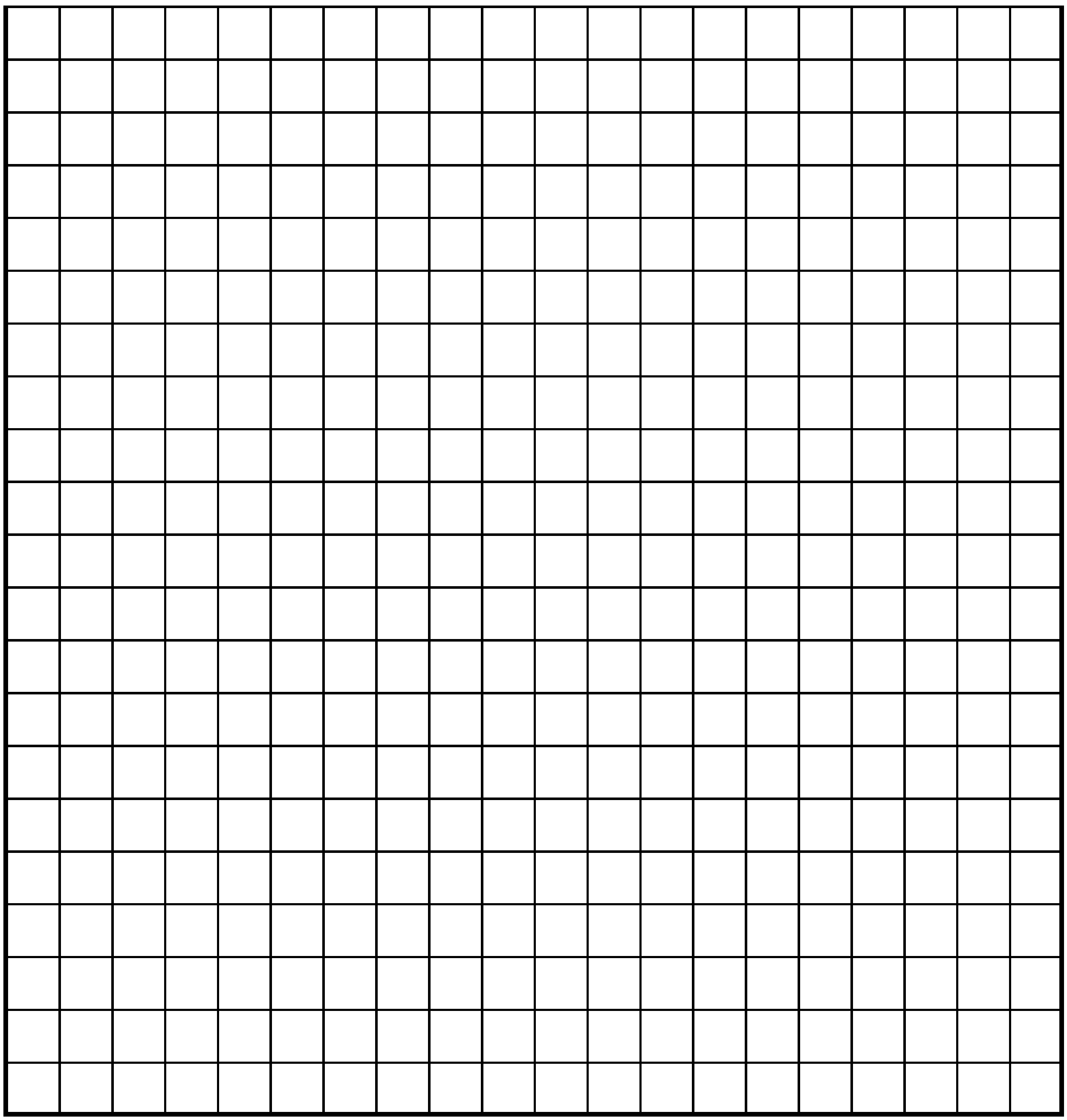


***Figure 3.*** *Force versus Vertical Deflection*

11. Draw a line of best fit through the data points. What type of relationship best describes the graph you drew?

12. Determine the slope of the line of best fit from your graph. Be sure to include units. Give this slope the symbol k. How does your k value compare to those found by groups around you? What does the slope of the line of best fit represent? Use the units of the slope in the description of its meaning. Relate the meaning of the slope to this particular lab and meter stick. Use your specific slope as an example.

13. Determine an equation that best represents the function shown on your graph. Be sure to use the symbols F and $\Delta x$. What is your y-intercept, and what does it mean? Should your equation have a y-intercept of 0 Newtons? Explain why or why not.

## Extension Activities

1. Consider what would happen if you used a different cantilever. How would the results change if the meter stick was thinner or thicker? What if you used a cantilever with a completely different shape, such as a dowel rod? How would you expect the results for a metal meter stick to differ?

   Repeat the experiment with a different cantilever and hypothesize how the results would compare to the results for the original experiment. After completing the experiment, comment on if your hypothesis was correct or incorrect. Explain your answer.

   **Table 3:** Extension – Data Collection

| Mass of Attached Weight, *m* (g) | Vertical Height, $x_f$ (cm) | Vertical Deflection, $\Delta x = x_i - x_f$ (cm)* |
|---|---|---|
| 0 | $x_i$ = | 0 |
| 100 | | |
| 200 | | |
| 300 | | |
| 400 | | |
| 500 | | |

**For m= 0 g, $x_i = x_f$ ,therefore, Δx = 0 cm.*

   **Table 2:** Extension – Data Processing

| Mass of Attached Weight, m (kg) | Force Exerted by Cantilever on the weight, F = m·a (N) | Vertical Deflection, $\Delta x = x_i - x_f$ (m)* |
|---|---|---|
| 0.000 | 0 | 0 |
| 0.100 | | |
| 0.200 | | |
| 0.300 | | |
| 0.400 | | |
| 0.500 | | |

**Report Δx in meters.*

2. On the provided graph (Figure 4), label the x-axis as "Vertical Deflection (Δx)" and the y-axis as "Force (F)." Plot the deflection as a function of added mass. Refer to the deflection distance using the symbol Δx.

## Extension - Modeling Hooke's Law

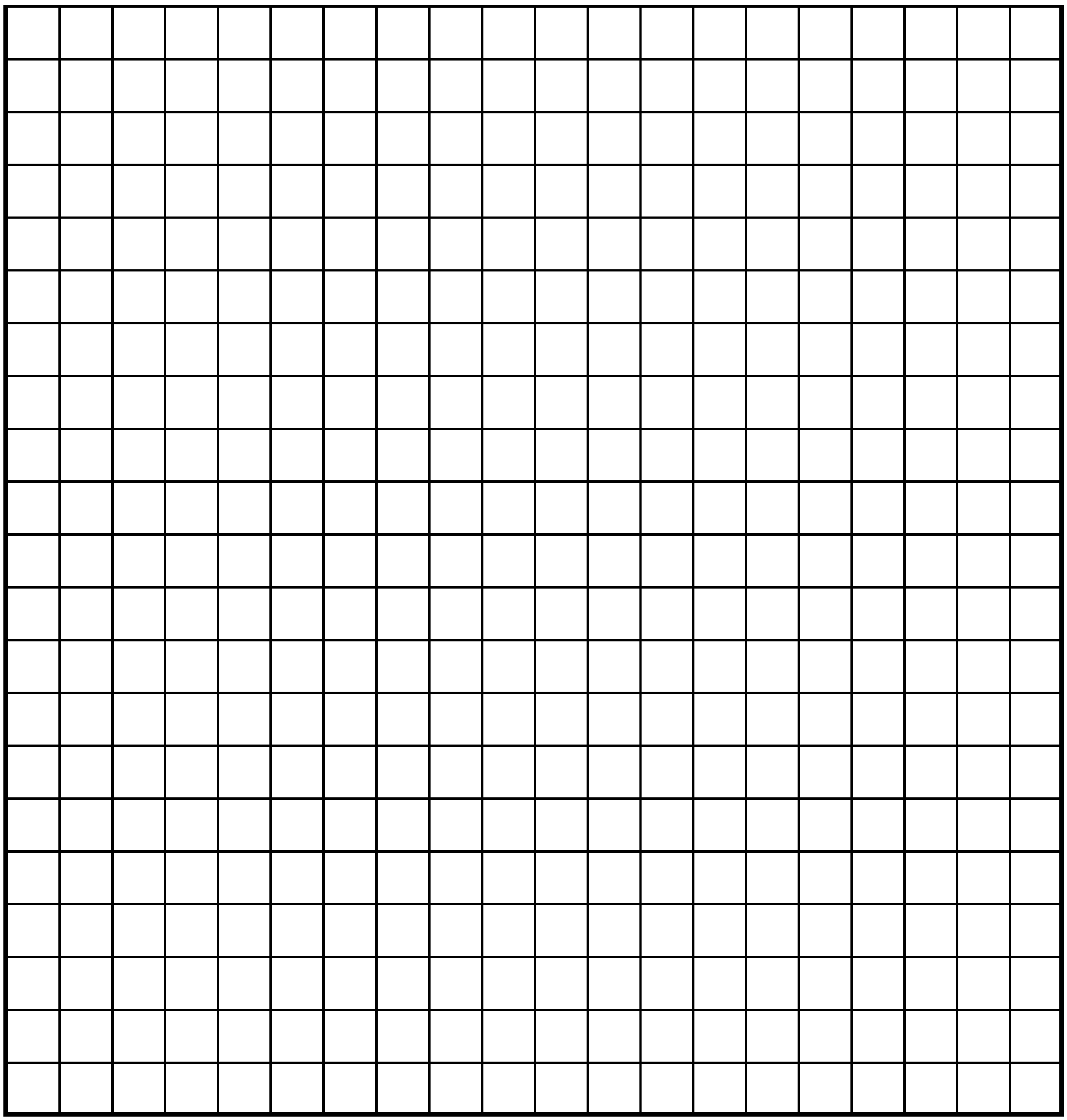


***Figure 4.*** *Extension - Force versus Vertical Deflection*

3. In the Data, Observation, & Analysis section, we asked you to draw a free-body diagram of the mass cantilever system. As an extension, draw a free body diagram of the cantilever in the system with mass added. Include the following: the force of the clamp, the force of gravity (for the hanging and clamped portions), applied force, and normal force.

## Assessment

1. Using your equation from question 13 in the Data, Observations & Analysis section, create a generalized formula that relates force, displacement, and the spring constant. Explain your reasoning.

2. What variables must be valid for a system to exhibit Hooke's law?

3. How is the resulting change in the system of force exerted on a cantilever similar to changes that would result from a force exerted on a spring?

4. What would Hooke's law look like if we used a less flexible cantilever? What about a more flexible cantilever? Explain your thinking. Can you think of a general rule for relating a material's physical characteristic to the spring constant?

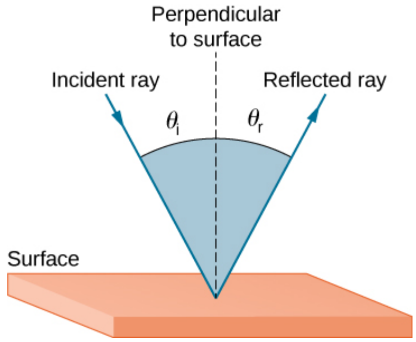


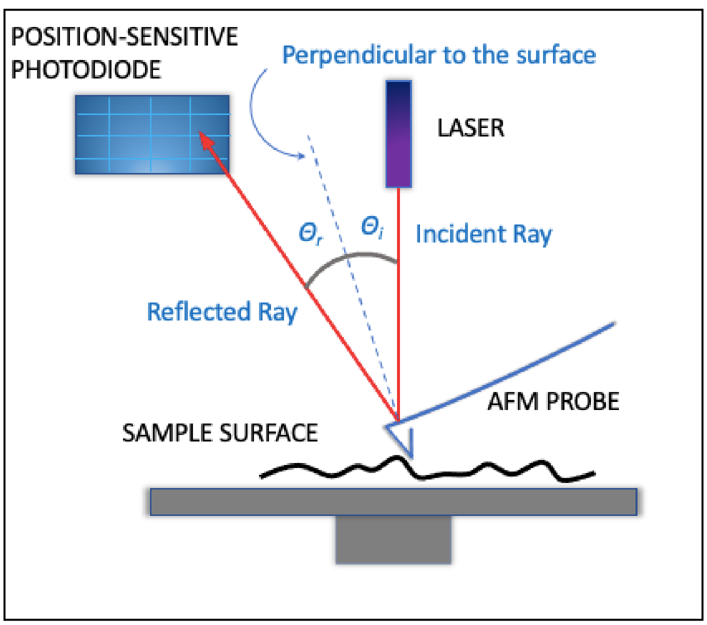

*Image Source*

# 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** $\Theta_i$ and **angle of reflection** $\Theta_r$ 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.

---

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 $\theta_i$ and the angle of the reflected ray $\theta_r$ .

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 $\alpha$. Rewrite the equation in terms of $\theta_i$.

6. Do you predict any correlation between the variables $x_f$, $y_f$, $\theta_i$, 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.

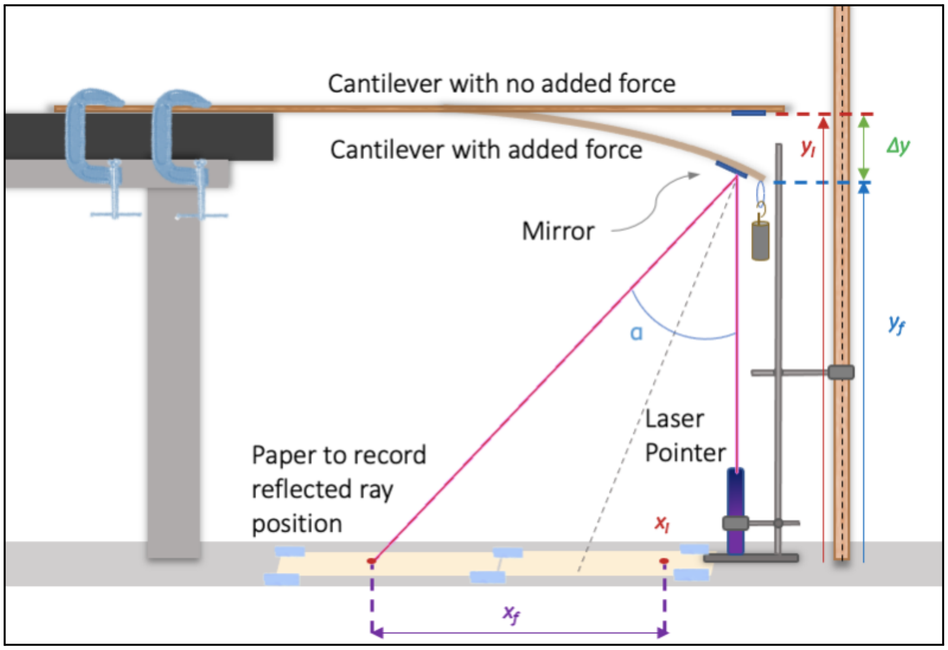



***Figure 2:*** *Experimental setup*

**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 $\Delta y$ ($\Delta y = y_i - y_f$).

    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 $\theta_i$ 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, Δ*y* (cm)** | **Horizontal Position of the Reflected Ray, $x_f$ (cm)*** | **Ratio of Horizontal to Vertical Position, $\frac{x_f}{y_f}$** | **Angle of Incidence, $\theta_i$ (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 $\theta_i$ (degrees)." Plot the angle of incidence as a function of added mass.

**Relationship Between Angle of Incidence and Added Mass in a Cantilever**

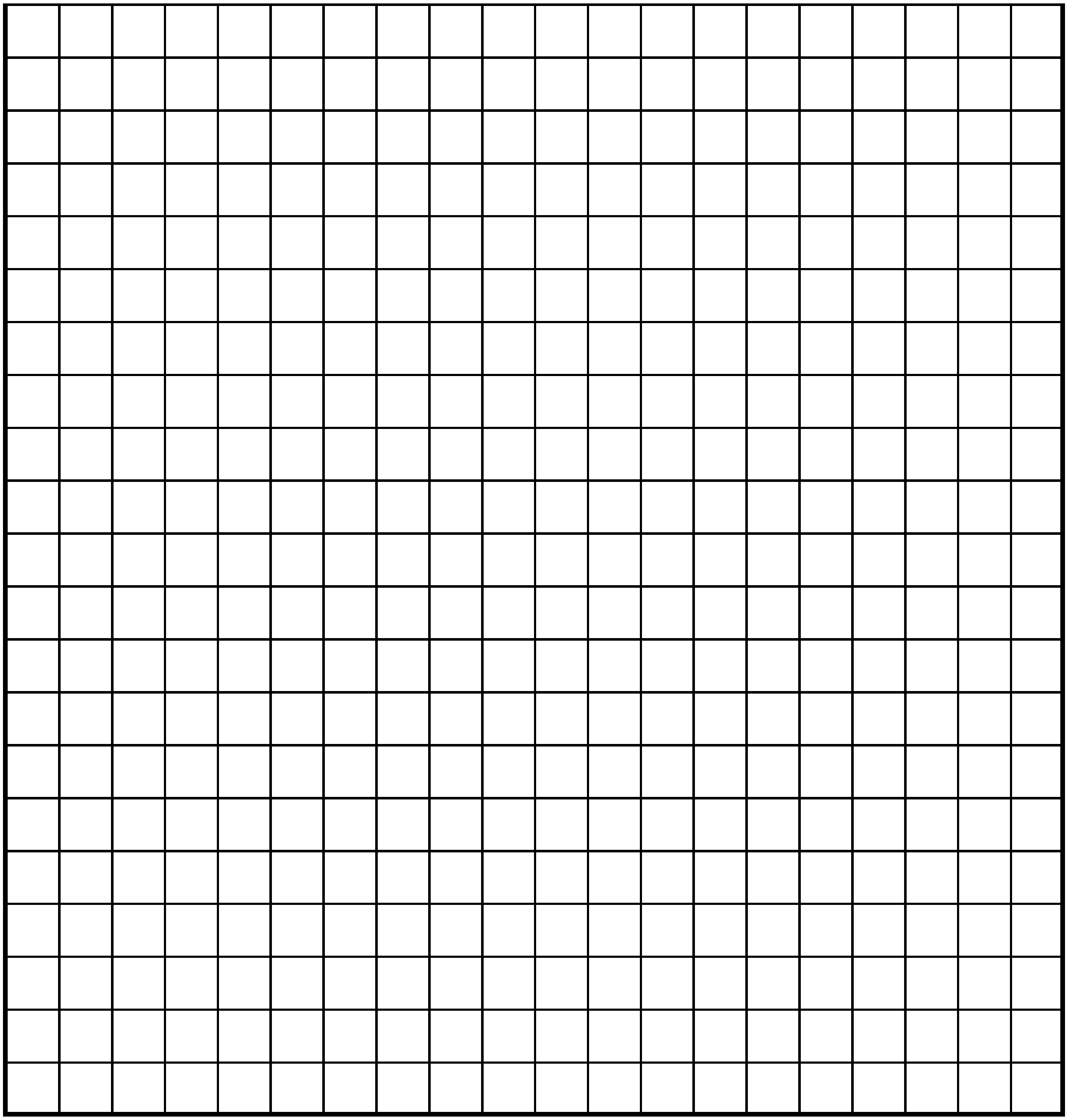


***Figure 3.*** *Angle of Incidence versus Added Mass.*

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 $\theta_i$ (degrees)" and the vertical axis as "Vertical Deflection $\Delta y$ (cm)." Plot the vertical deflection as a function of the angle of incidence.

**Relationship Between Deflection and Angle of Incidence in a Cantilever**

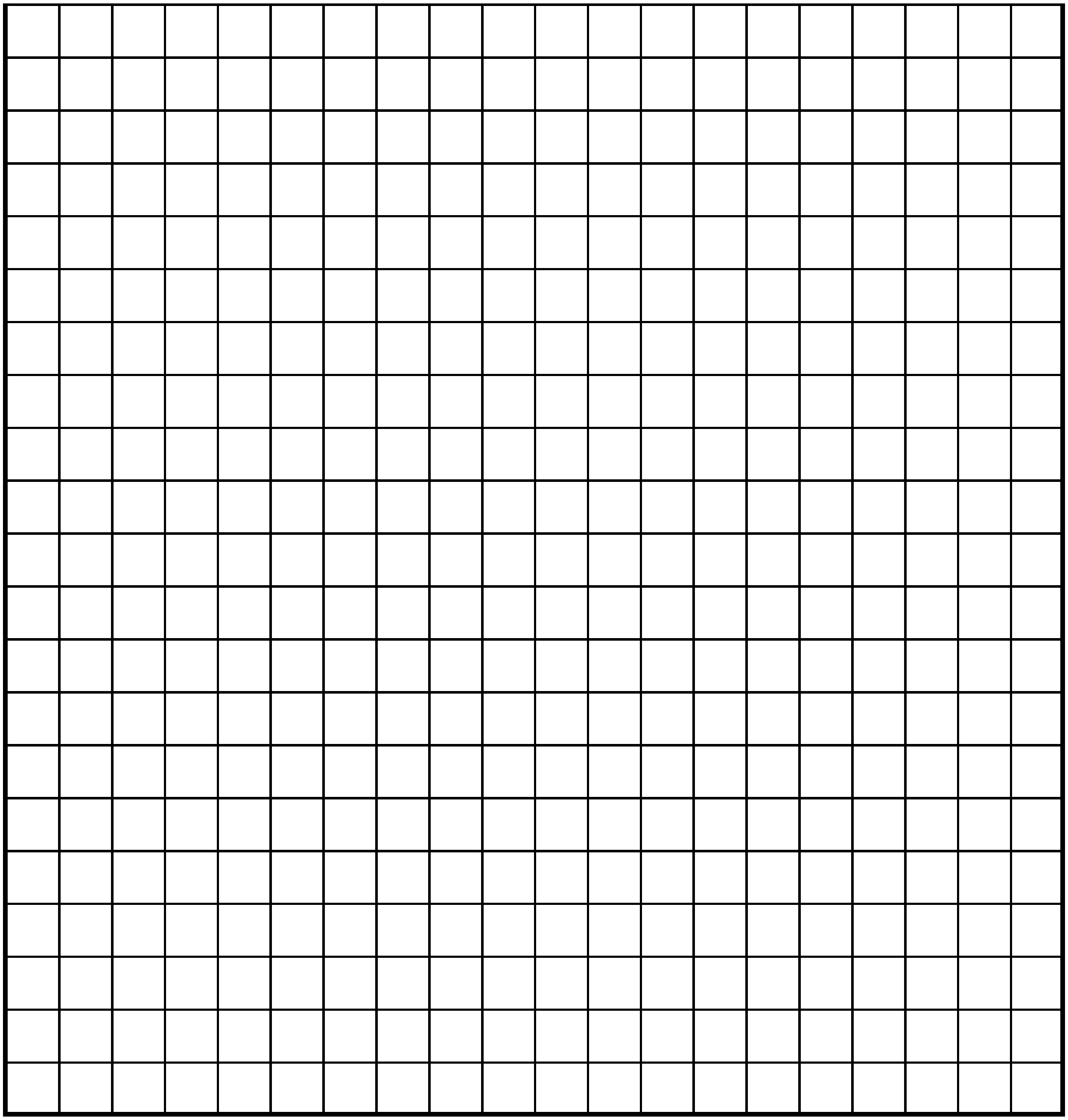


***Figure 4.*** *Angle of Incidence versus Vertical Deflection.*

## 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?

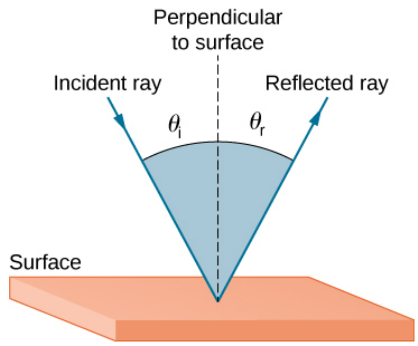


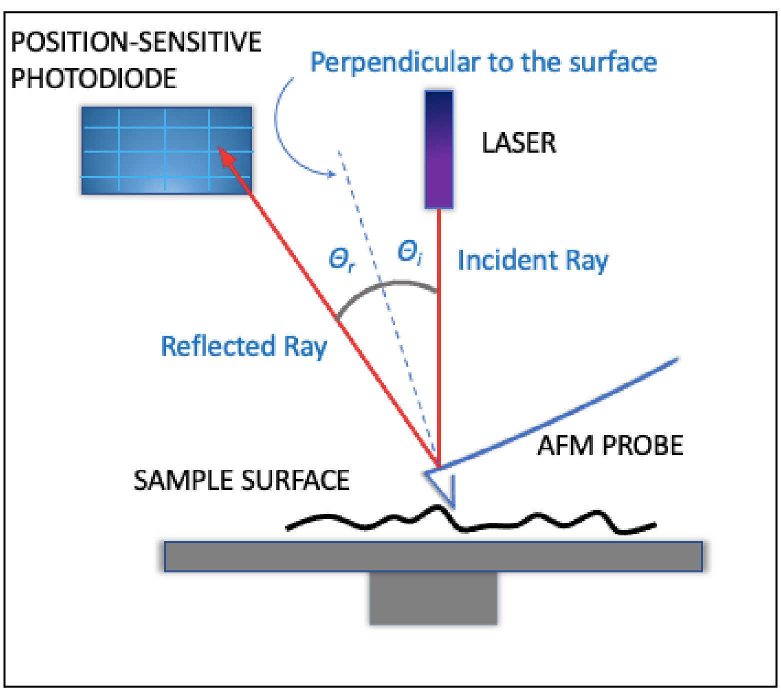

*Image Source*

# Atomic Force Microscopes (AFMs)

## PART 4: Statistical Analysis: Understanding How AMFs Use Optics & Reflected Light to Determine Sample Properties

### Introduction

**Atomic force microscopes (AFM)** 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 fluctuations in the **angle of incidence** $\Theta_i$ and **angle of reflection** $\Theta_r$. Thus, tracking the changes. As the AFM passes over a raised surface, the PSPD records the cantilever deflection and the resulting change in the angle of incidence.




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

From the equations derived in the last lesson, we can calculate (as a function of added mass) the expected values of horizontal deflection, vertical deflection, or angle of incidence. Then we can use statistical analysis to determine the effectiveness and significance of our instrumentation for mapping nanometer-sized surfaces.

**In this lab, you will learn how to:**

- 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.

## 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 in locations in which 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
- Protractor
- laptop or calculator (to do the $\chi^2$ test and look up the $\chi^2$ table for p-values)
- writing utensil

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

## Activity Introduction

During this activity, you will 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 do five tests, with a different mass added to the end of the cantilever each time. 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. Considering the lab setup and your previous experience with cantilever systems. What are some sources of error? Explain your reasoning.

3. Do you predict the relationship between $x_f$, $y_f$, $\theta_i$ and the added mass to be the same as the last time? Explain your reasoning.

4. 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. Tape a piece of string of length 1 m to the top of the free end. Make sure the string aligns with the point where the laser hits the mirror.

Laser: Attach the laser pointer to the ring stand with a clamp, so 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.

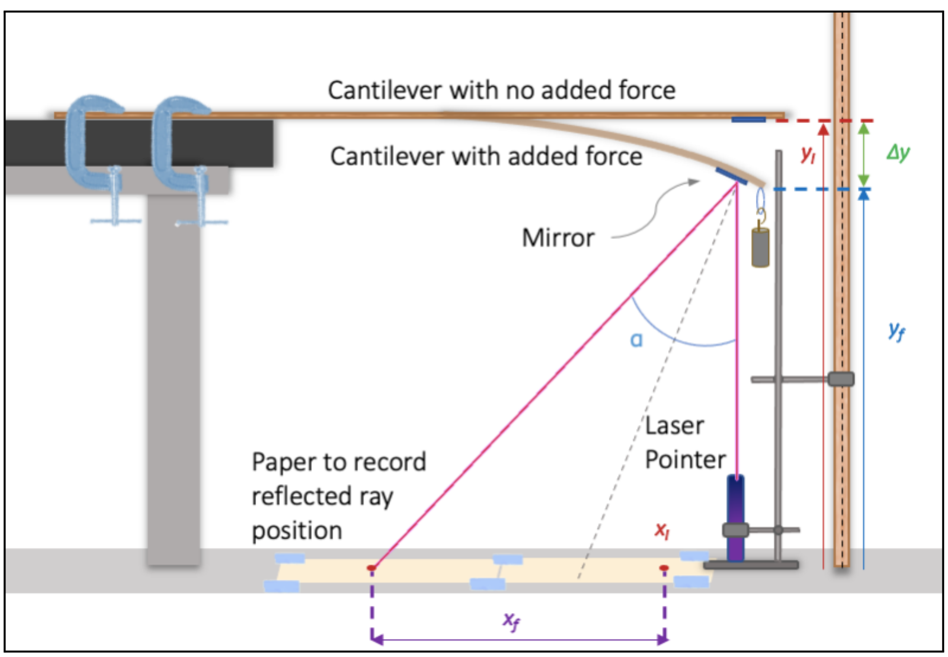


***Figure 2:*** *Experimental setup*

**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 $x_i$ (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 $y_i$. We will measure the distance the reflected beam hits the floor from this position as mass is added to the cantilever.

**Step 3: 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: Exert force on the cantilever, record new height & angle**
Attach the 50 g mass to the string. Place the center of the protractor on the point $y_i$. Using the string, measure the angle α (where $\alpha = \Theta_i + \Theta_r$). Record the mass (in grams) and corresponding angle as α in Table 1. Measure the height of the free end of the meter stick, measuring upward from the floor. Record the mass (in grams) in Table 1.

**Step 5:** Repeat Steps 3 and 4 using 100g, 150g, 200g, 250g, and 300g.

## Data, Observations, & Analysis

1. Estimate how much the cantilever deflected with no added mass. How about 100g of added mass?

2. 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 $\Delta y$ ($\Delta y = y_i - y_f$).
    b. Record the horizontal distance of the reflected ray relative to the initial position $x_i$.
    c. Calculate the ratio of the horizontal to the vertical position using $x_i / y_i$.

3. Using your string and protractor, measure angle α in degrees and record it in Table 1.

**Table 1:** Data Collection & Analysis

| **Mass of Attached Weight, *m* (g)** | **Horizontal Position of the Reflected Ray, $x_f$ (cm)*** | **Vertical Height, $y_f$ (cm)** | **Angle of Incidence, $\theta_i$ (degrees)** |
|---|---|---|---|
| 0 | $x_i$ = 0 | $y_i$ = | 90° |
| 50 | | | |
| 100 | | | |
| 150 | | | |
| 200 | | | |
| 250 | | | |
| 300 | | | |

**For m= 0 g, $x_i = x_f$ and $\Theta_i = 90°$. All other values of $x_f$ are measured as the distance from $x_i$ and $\Theta_i$ is measured each time.*

4. Calculate the new height for each added mass using trig functions. Then find the deflection value by subtracting $y_f$ from the initial height. Record your values in the following table:

| **Mass of Attached Weight, *m* (g)** | **Angle of Incidence, $\theta_i$ (degrees)** | **Vertical Height Δy (cm)** | **Deflection $\Delta y = y_i - y_f$ (cm)** |
|---|---|---|---|
| 0 | | | |
| 50 | | | |
| 100 | | | |
| 150 | | | |
| 200 | | | |
| 250 | | | |
| 300 | | | |

5. Do the vertical deflection values make intuitive sense? Explain your reasoning.

6. On the provided graph (Figure 3), label the horizontal axis as "Force (N)" and the vertical axis as "Vertical Deflection (cm)." Plot the angle of incidence as a function of added mass.

## Relationship Between Force and Vertical Deflection

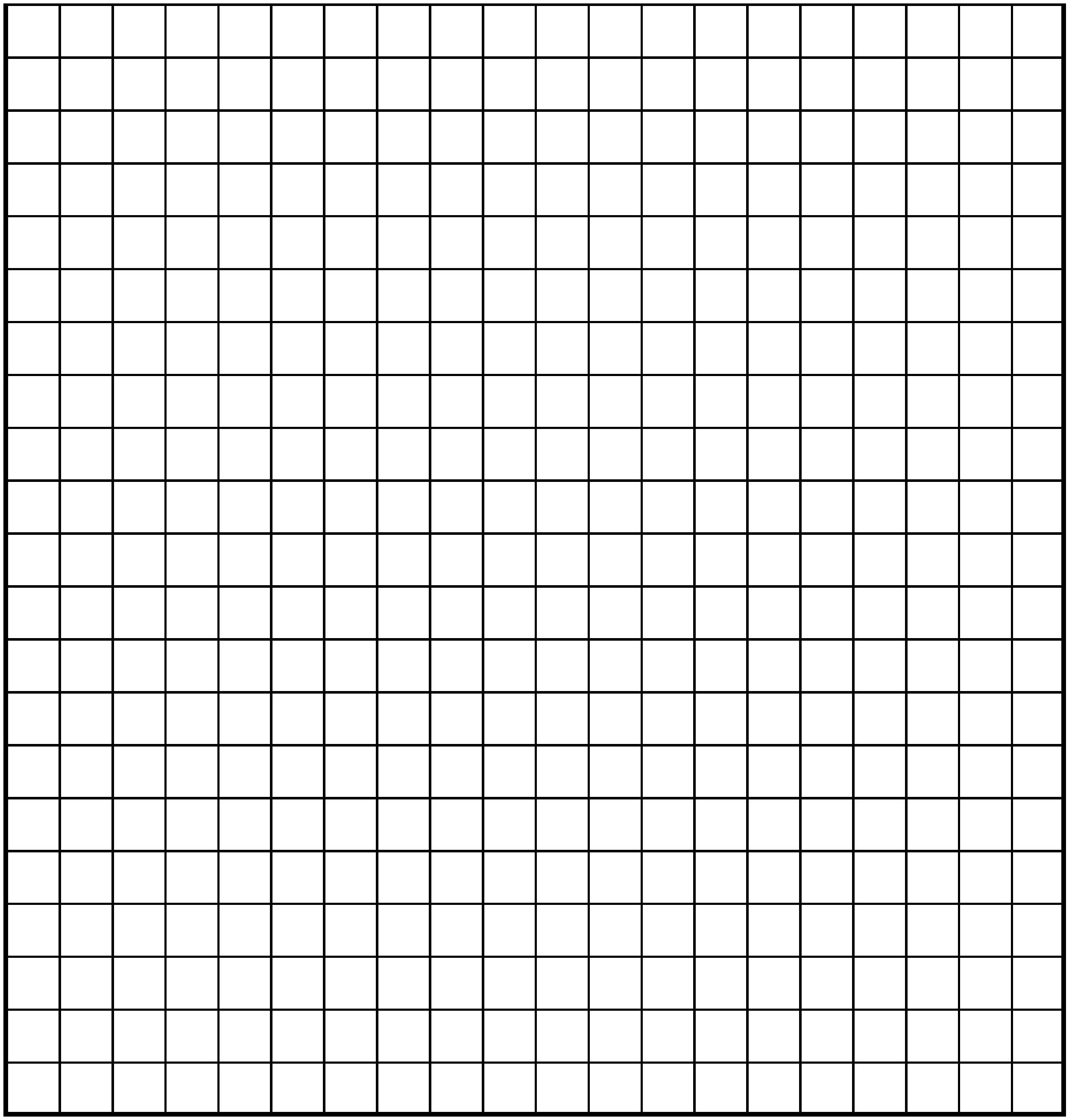

***Figure 3.*** *Force versus Vertical Deflection.*

7. On the same graph (Figure 3), use a different color to plot the expected vertical deflections for a given force. How do the expected values compare with the observed values? Do your numbers make sense? Why or why not?

8. Using your trig equation from the previous lesson, find the expected angles and record them in the following table with the corresponding mass.

| **Mass of Attached Weight, *m* (g)** | **Expected Angle of Incidence, $\theta_{Ei}$ (degrees)** |
|---|---|
| 0 | |
| 50 | |
| 100 | |
| 150 | |
| 200 | |
| 250 | |
| 300 | |

9. Compare your expected angles with your measured angles. Do they seem similar, or are they different? If they were different, how could this impact the calculations for vertical deflection?

**Statistical Analysis**

We can use Person's Chi-Squared Test to determine if there is a statistically significant difference between the expected and observed values in one or more categories of a contingency table. To perform Person's Chi-Squared Test, we need the degrees of freedom. The degree of freedom is the least number of values you can know to solve for the Chi-Squared value. In this case, degrees of freedom, denoted as df, is equal to the sample space (denoted as n) minus one.

$$df = n - 1$$

A contingency table is a matrix that displays the multivariate frequency distribution of the variables. The following formula determines Person's Chi-Squared value:

$$\chi^2 = \sum_{i=1}^{n} \frac{(O_i - E_i)^2}{E_i}$$

10. In the following consistency tables, copy your expected and observed values.

| **Mass of Attached Weight, *m* (g)** | **Angle of Incidence, $\theta_i$ (degrees)** | **Expected Angle of Incidence, $\theta_{Ei}$ (degrees)** |
|---|---|---|
| 0 | | |
| 50 | | |
| 100 | | |
| 150 | | |
| 200 | | |
| 250 | | |
| 300 | | |

11. Write your $\chi^2$ value and degrees of freedom:

    a. $\chi^2$ =

    b. df =

## Assessment

1. Using a Chi-Squared Table or Chi-Squared calculator, state your p-value and significance level. What does your p-value tell you?

2. State your conclusion based on the results from the Chi-Squared Test.

3. According to your conclusion, would you recommend this instrumentation method for finding vertical deflection? Why or why not?

4. What changes could you make to better the experimental setup? What statistical tests could you run to make sure your experimental setup is an improvement?