The Quantum Nature of Waves

Thrust 3: Coherent Quantum Interfaces

7th - 8th Grade

Version 2. 03/20/2022

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About the Quantum Foundry

The Quantum Foundry was founded at UC Santa Barbara by the National Science Foundation in 2019 to develop and explore materials for exploring quantum information science.

Quantum information science (QIS) combines information transmission, analysis, and processing with the principles of quantum physics. The field was born in the mid-1990s and has grown rapidly as it demonstrates the potential to revolutionize the current state of the art in computation and information technology. By harnessing the peculiarities of quantum mechanics, QIS will allow us to develop unbreakable codes and computers that operate hundreds of million times faster than today's supercomputers.

The Quantum Foundry brings together researchers from universities and industry to discover advances in materials science that are needed to power the coming age of quantum-based electronics. Additionally, it aims to train the future quantum workforce and educate students about QIS from a young age, as is the goal of this kit!

The Quantum Nature of Waves Storyline

Activity #1 Art in Quantum	**Lesson Question**	How does light from a laser behave? How can we create a creative art piece using the properties of lasers?
	Phenomena	Lasers are concentrated waves of light that in phase with each other and behave in interesting ways under different conditions.
	What We Do and Figure Out	Students compare a laser pointer and flashlight to understand the unique properties of light. They then explore three different phenomenon using laser pointers and either create an art piece or explore a black box that will serve as an anchoring point for the entire module. Students learn that light behaves as a wave and that lasers produce a concentrated beam of light where all waves of light line up with each other.
	Connection to the Quantum Foundry	The study of light is a large component of the research conducted at the Quantum Foundry, and lasers are commonly used in their research and serve as a useful tool to understand quantum properties.

Navigation: Now that students have learned about how light behaves and explored different phenomenon with lasers, they will dive into each phenomenon to learn the science behind the behavior.

Activity #2 Polarized Filters	**Lesson Question**	How does light behave when it passes through polarized filters?
	Phenomena	Light is partially absorbed by a single polarized filter, but is completely absorbed by two polarized filters placed perpendicularly to each other.
	What We Do and Figure Out	Students explore light passing through one, two, and three polarized filters. They learn that approximately 50% of light passes through one and two filters; however, when the second filter is rotated to a perpendicular position 100% of light is blocked. When a third filter is placed in between the perpendicular filters at a diagonal angle, some light starts to pass through all three filters.
	Connection to the Quantum Foundry	This activity demonstrates how filters can be used to dictate the direction of light waves. When a third filter is introduced, it models a state of superposition which is an important concept in quantum research where a qubit may be a 1 or a 0 at the same time.

Navigation: Students have learned how some materials can absorb, reflect, or transmit light waves. They will now investigate what happens when light encounters a barrier between two materials (air and hair) that causes the light to change behaviors.

Activity #3 Diffraction Patterns	
	Lesson Question
	How can we use diffraction patterns of light to measure the width of a hair?
	Phenomena
	Laser beams when shone past hair create a diffraction pattern due to the wave nature of light.
	What We Do and Figure Out
	Students learn about diffraction patterns created by light waves when a laser beam crosses a strand of hair. They learn that this pattern is created by the interference of two light waves intersecting. Students then use this phenomenon to measure the width of their own hair.
	Connection to the Quantum Foundry
	Researchers at the Quantum Foundry use the phenomenon of interference that leads to laser diffraction to make measurements when developing new materials to improve communication and computing technologies.

Navigation: Students have learned about the diffraction patterns light makes when it crosses a strand of hair. They will not investigate the diffraction patterns made when light is shone through an

Activity #4 Aperture Diffraction	
	Lesson Question
	How does a diffraction pattern change when a laser beam is shone through different sized apertures?
	Phenomena
	Diffraction patterns of a laser beam are smaller when a laser is shone through a larger aperture and larger when shone through a smaller aperture.
	What We Do and Figure Out
	Students conduct an investigation by measuring the diffraction patterns when they shine a laser through various sized apertures. They discover that the smaller the aperture, the larger the diffraction pattern.
	Connection to the Quantum Foundry
	This activity models how quantum scientists can only measure one characteristic of quantum particles at a time. In this case, if the aperture is smaller we can know where a particle of light is with confidence;

	however, as shown by a larger diffraction pattern, we can't know with confidence the direction of motion of the particle of light.

Navigation: Students have learned about how light passes through a polarized filter and creates a diffraction pattern under two different conditions. Students will use their new understandings to revisit their initial art pieces and write art museum captions to explain their

Activity #5 Final Reflections	**Lesson Question**
	How can we use our new understanding of light to explain the art pieces made in Activity #1?
	Phenomena
	Lasers are concentrated waves of light that in phase with each other and behave in interesting ways under different conditions.
	What We Do and Figure Out
	Students revisit the art pieces they made in Activity #1 and have the opportunity to make changes based on their experiences throughout this module. Afterwards, they write a caption explaining the methods they used to create the art piece, the science behind the phenomenon they used, and the connection to the Quantum Foundry.
	Connection to the Quantum Foundry
	The connection between art and STEM is important to the Quantum Foundry and in fact, many researchers compete in the Art of Science competition hosted by UCSB every year.

Materials List

	Activity #1	Activity #2	Activity #3	Activity #4	Activity #5
Flashlight	⚛				
Laser pointers (2 per group)	⚛	⚛	⚛	⚛	⚛
Polarized filters (3 per group)	⚛	⚛			⚛
Hair frames (1 per student)	⚛		⚛		⚛
Aperture cards (1 per pair)	⚛			⚛	⚛
Photo capturing device (1 per group)	⚛				⚛
Meter/yard stick			⚛		
Ruler				⚛	
Tape	⚛		⚛		⚛
Scissors	⚛		⚛		⚛
Large paper taped on wall			⚛	⚛	

All videos can be found here: https://ucsb.box.com/s/olonu8u0h4m26e5gja8s2f8n4efq84si

Shopping Suggestions:

Laser pointers (Red 650nm) can be purchased online. They are least expensive in bulk. Try Sci-Supply

Polarizing film like this packet found on Amazon

Quantum Laser Explorations

Activity #1- Art in Quantum

50 min

Students learn about how laser pointers work and investigate three different phenomenon lasers can be used in to make a piece of art that will serve as the anchoring point for subsequent activities.

Learning Goals
Students will develop a conceptual model of light as a wave.
Students will develop a conceptual model of how lasers differ from general light bulbs.

<table>
<tr><th colspan="3">NGSS Connections</th></tr>
<tr><td colspan="3">MS-PS4-1. Use mathematical representations to describe a simple model for waves that includes how the amplitude of a wave is related to the energy in a wave.</td></tr>
<tr><th>Science and Engineering Practices</th><th>Disciplinary Core Ideas</th><th>Crosscutting Concepts</th></tr>
<tr><td>Developing and Using Models to describe a phenomenon</td><td>PS4.B: Electromagnetic Radiation
• A wave model of light is useful for explaining brightness and color</td><td>Structure and Function
• Structures can be designed to serve particular functions by taking into account properties of different materials, and how materials can be shaped and used.</td></tr>
</table>

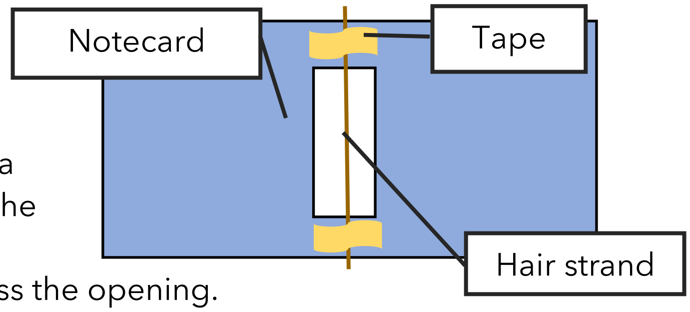
<table>
<tr><th colspan="2">Materials</th></tr>
<tr><th>For Teacher Demonstration</th><th>For Student Activity</th></tr>
<tr><td>Flashlight</td><td><u>Intro to Lasers Worksheet</u> (1 per student)</td></tr>
<tr><td>Laser pointer (red or green)</td><td rowspan="5">Tray or container (per group) prepared with:
• 2 laser pointers (red or green)
• 2 polarized filters
• 2 aperture cards
• 2 Hair frames
• Photo capturing device (i.e., iPad or computer)</td></tr>
<tr><td>1 Hair frame (see preparation for how to make)</td></tr>
<tr><td>1 Polarized filter</td></tr>
<tr><td>1 Aperture card (see preparation for how to make)</td></tr>
<tr><td>Lesson Videos</td></tr>
</table>

Quantum Laser Explorations

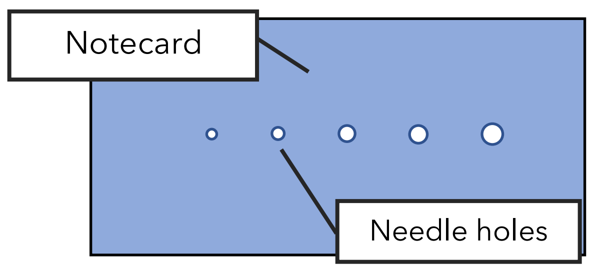
Activity #1 | Activity #2 | Activity #3 | Activity #4 | Activity #5

Activity Preparation

1. Create Hair Frames
   a. To create these, you will need: Tape, a 3" x 5" notecard, a strand of hair.
   b. Take a 3" x 5" notecard and cut a hole approximately 1.5" x 1" in the center.
   c. Tape a piece of hair tightly across the opening. Loose hairs will not work, make sure it is as taut as possible.
   d. If you are uncomfortable preparing these slides for students, hand them pre-cut notecards and have them tape their own hairs across the openings.



2. Create Aperture Cards
   a. To create these, you will need: 3-4 sewing needles of various sizes, a 3" x 5" notecard.
   b. Using the smallest sewing needle, carefully create a hole in a 3" x 5" notecard by gently pushing the needle through. Try to not wiggle the needle too much as you want a clean circular hole.
   c. Using sewing needles of various sizes, create 2-4 more holes at least .25 inches away from the initial hole in order from smallest to largest diameter of needle. Make sure the largest hole is still smaller than the beam from the laser pointer.



3. Print _Intro to Lasers_ worksheets

4. Download or buffer the _Quantum Foundry Intro_ and _Intro to Lasers_ videos

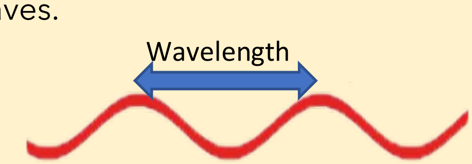
Quantum Laser Explorations

Activity #1 | Activity #2 | Activity #3 | Activity #4 | Activity #5

Background Knowledge

Lasers, while commonly found at concerts and as toys to tease your cat, are extremely useful in the world of *quantum mechanics* as a tool to measure small objects and understand quantum properties. Light travels as a wave with different colors of light having different wavelengths. For example, wavelengths of about 400nm create a purple light while wavelengths of 700nm create red light. When a flashlight is shone, light of all wavelengths is produced which creates the white beam of light. Lasers are unique in that they emit light of similar wavelengths that travel together with peaks and valleys of the wave lined up, or what scientists call *in phase*. This causes a very narrow and bright beam of light to be produced when a laser pointer is shined at a wall. Since all of the light waves in a laser are in phase, scientists can use lasers to measure small objects and create efficient and accurate communication devices.

Key Vocabulary

Quantum Mechanics	A theory in physics that describes the nature of atoms and sub-atomic particles. It is the foundation of all quantum sciences.
In phase	When waves of light of the same wavelength (color) align so that the peaks and valleys of the wave are all lined up, they are considered in-phase. 
Laser	Laser is an acronym that stands for "**L**ight **A**mplification by **S**timulated **E**mission of **R**adiation." A laser pointer is a device that causes atoms to emit light of certain wavelengths in a very narrow beam.
Wavelength	This is the distance between identical points (i.e., the peaks) of two successive waves. 

Quantum Laser Explorations

Activity #1 | Activity #2 | Activity #3 | Activity #4 | Activity #5

Introduction to the Quantum Foundry

1. Ask students if they have visited the University of California, Santa Barbara (UCSB) campus.

2. Recently, UCSB has opened up a multi-million-dollar institution called the Quantum Foundry. Let's learn more about this from Dr. Galan Moody, a lead researcher in the Quantum Foundry.

3. Play the Quantum Foundry Intro video.

Engage

1. **Students observe a phenomenon.** Turn off the lights in the classroom and shine a flashlight and a laser pointer at the front of the classroom. Encourage students to not stare at the laser as it can cause headaches. Ask students to make observations about similarities and differences between the two lights and their sources and write down their ideas in the "Initial Ideas Venn Diagram" on the *Intro to Lasers* worksheet.

2. Prompt students to discuss their observations of the two light sources. What are some similarities and differences between the light itself? What are some similarities and differences between the sources of the light?

3. Explain that over the next few lessons, students will explore lasers and learn about the properties of lasers that make them unique compared to a normal flashlight so scientists can use them to study quantum materials.

Quantum Laser Explorations

Activity #1 | Activity #2 | Activity #3 | Activity #4 | Activity #5

Introduction to Light

1. Elicit student ideas about light. What is light? Where does it come from? Are there different types of light? How do we get different colors of light?
   a. Some students may know that light is a form of energy and that it behaves as a wave and a particle. Highlight these ideas if they come up.

2. Show the Intro to Lasers video. While students watch the video, encourage them to answer the questions on the "How Light Works" section of the *Intro to Lasers* worksheet.

3. After the video, ask students to share their answers.

Quantum Laser Explorations

Activity #1 | Activity #2 | Activity #3 | Activity #4 | Activity #5

Art Exploration

1. Now that we know how lasers work, explain that lasers can be used in a variety of different ways. Today, students will use laser pointers to create an art piece to guide our future investigations into light.

2. **Demonstrate**. There are three main behaviors of lasers we will learn about:
    a. The first is a pattern that is created when you shine a laser at a thin string or hair. Hold up the frame with the hair/string and shine the laser pointer at the paper on the wall, making sure to hit the hair with the laser beam. You should see the light scatter to the sides as you hit the hair with the laser pointer. You may need to move towards or away from the wall depending on your laser pointer to get a clear scatter pattern.
    b. The second is a pattern that is created when you shine a laser pointer through a small aperture or hole. Hold up the frame with small holes poked through it and shine the laser pointer at the wall passing the light through one of the holes. You should see the light create a round fuzzy pattern on the wall. You may need to move towards or away from the wall depending on your laser pointer to get a clear pattern.
    c. The third is changes in intensity that happen when you pass a light through a polarized filter. Hold up a polarized filter and shine the laser pointer at the wall passing the light through the filter. You should see the laser pointer get 50% dimmer.

Teacher note: This demonstration can be extended by asking students to predict what will happen to the laser pointer light beam before each demonstration.

Quantum Laser Explorations

Activity #1 | Activity #2 | Activity #3 | Activity #4 | Activity #5

3. **Introduce today's challenge.** Students will create an art piece using the three different methods demonstrated above. Encourage students to work together to layer multiple effects of laser pointers at one time. Students should use a digital recording device (i.e., iPad or computer) to capture their laser design.
    a. Safety note: Do not shine laser pointer into any one's eyes as this can cause permanent damage to their eyes. Students may experience headaches if they stare at the laser pointer light shining on the wall for too long so encourage frequent breaks if needed.

Emphasize this safety point for students

4. Organize students into teams (ideally with 3-4 students per group). Hand out materials to each group of students. Each group should receive:
    a. Two laser pointers
    b. Two polarized filters
    c. Two string frames
    d. Two aperture cards
    e. Photo capturing device (i.e., iPad or computer)

5. Allow students to work on their art designs for 10-15 minutes encouraging them to experiment with the lasers and materials and see what fun designs they can make. If students seem stuck, encourage them to make multiple designs, layer different techniques, play with the camera settings, etc.

6. **Discuss.** Ask students to share out their final design creations with the class an explain the techniques used to make them.

Quantum Laser Explorations

Activity #1 › Activity #2 › Activity #3 › Activity #4 › Activity #5

Wrap-Up

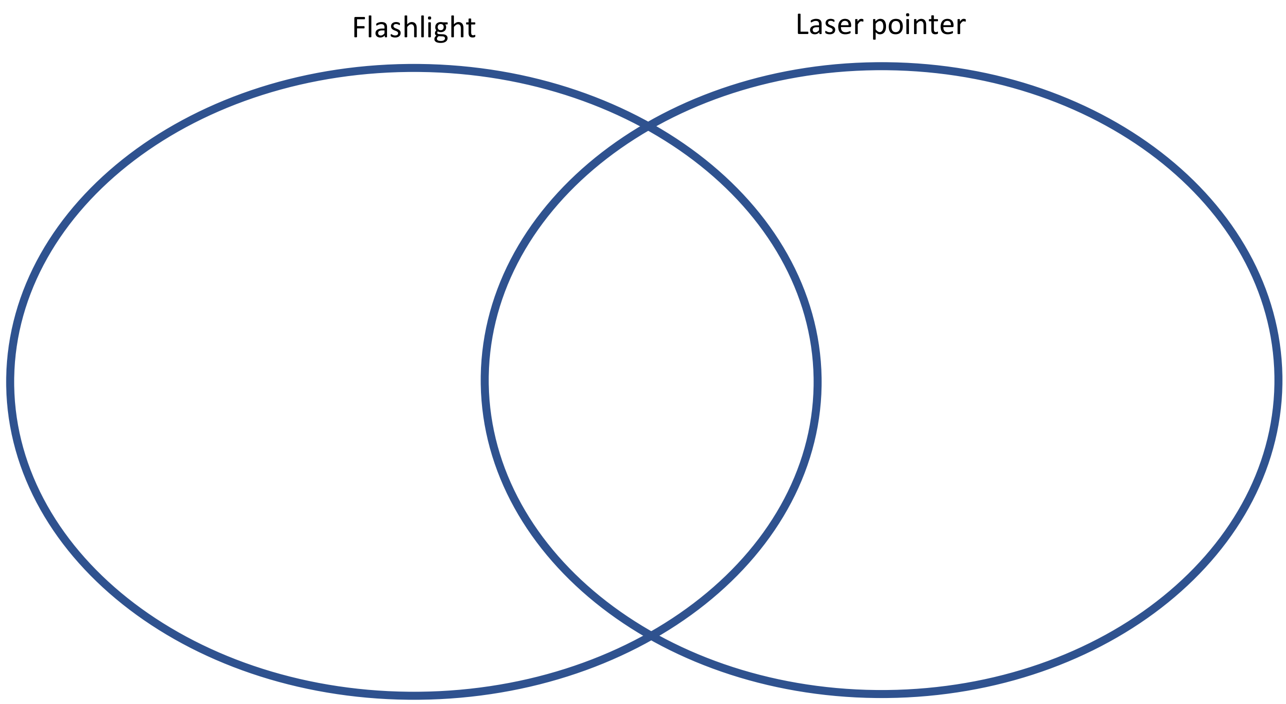
1. Let students know that they will further explore the three main phenomenon they saw today over the next few lessons. They will also learn about how scientists at UCSB's Quantum Foundry use these techniques and phenomenon to study quantum materials.

Be sure to keep the photos of the student art creations as they will revisit them in Activity #5.

Name: ___________________________________ Date: ____________________

Intro to Lasers

Fill out the Venn Diagram comparing a flashlight and laser pointer.



Answer the following questions while watching the *Intro to Lasers* Video.

1. How does light behave?

2. What is the light we can see called?

3. What about light causes different colors?

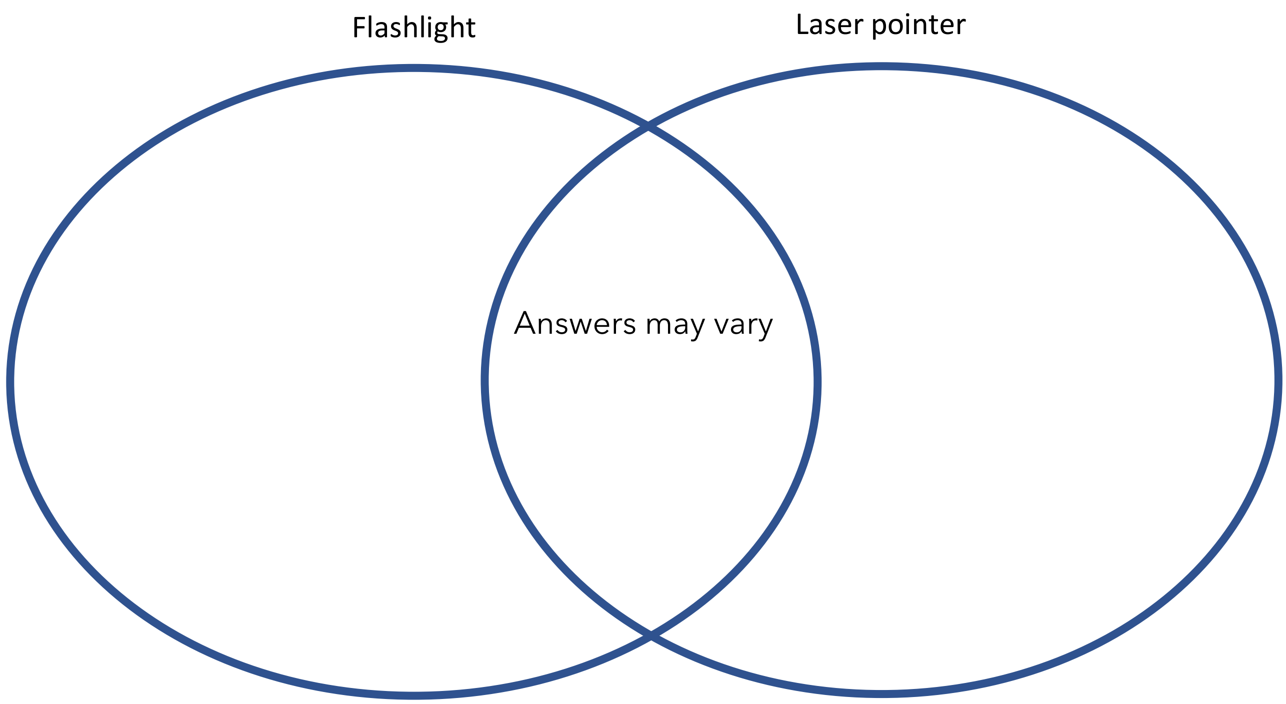
4. What makes laser beams special compared to your average flashlight?

5. Draw a model of how the light comes out of a laser pointer.

Name:_<u>Answer KEY</u>__________________________ Date: ______________________

Intro to Lasers

Fill out the Venn Diagram comparing a flashlight and laser pointer.



Answer the following questions while watching the *Intro to Lasers* Video.

1. How does light behave?
   As a wave or a particle.
2. What is the light we can see called?
   Visible light
3. What about light causes different colors?
   Wavelength
4. What makes laser beams special compared to your average flashlight?
   The laser orients the waves of light so they are *in phase* with each other, or rather the peaks and valleys line up within the beam of light.
5. Draw a model of how the light comes out of a laser pointer.
   Answers will vary. Note a representation of waves of light being aligned with peaks and valleys matching, single color light being emitted.

Quantum Laser Explorations

Activity #2- Polarized Filters

50 min

Students learn about how laser pointer light beams alter when shone through polarized filters. They also learn about the unique structure of polarized filters and how this structure can be used in quantum science.

Learning Goals
Students will develop a conceptual model of polarized filters.
Students will understand how multiple polarized filters affect a laser beam.
Students will understand how polarized filters model a state of superposition.

NGSS Connections		
MS-PS4-2. Develop and use a model to describe that waves are reflected, absorbed, or transmitted through various materials.		
Science and Engineering Practices	**Disciplinary Core Ideas**	**Crosscutting Concepts**
Developing and Using Models to describe a phenomenon	**PS4.B: Electromagnetic Radiation** - When light shines on an object, it is reflected, absorbed, or transmitted through the object, depending on the object's material and the frequency (color) of the light	**Structure and Function** - Structures can be designed to serve particular functions by taking into account properties of different materials, and how materials can be shaped and used.

Quantum Laser Explorations

Activity #1 | Activity #2 | Activity #3 | Activity #4 | Activity #5

Materials	
For Teacher Demonstration	**For Student Activity**
Laser pointer (red or green)	*Polarized Filter Observations* Worksheet (1 per student)
3 polarized filters	Tray or container (per pair) prepared with: • 1 laser pointer (red or green) • 3 polarized filters
Lesson Videos	

Activity Preparation

1. Print *Polarized Filter Observations* worksheets- one per student.

2. Prepare polarized filters if not already completed.
    a. Polarized filters can be bought here.
    b. Cut sheets of polarized filter into approximately 3" x 4" rectangles. If purchased from the link above, no resizing is needed.
    c. Orient polarized filters so that they are all oriented in the same direction (when you hold two of the filters on top of each other, you should still be able to see through both filters). Draw a line using a sharpie or whiteboard marker on the filters so students can track the orientation of the filters.

3. Download or buffer the *Slinky Filters* and *Quantum Applications: Polarized Filters and Superposition* videos and the *Polarized Filter Slide Deck*

Quantum Laser Explorations

Activity #1 | Activity #2 | Activity #3 | Activity #4 | Activity #5

Background

Polarized filters are special types of filters made of long polymers arranged in a single direction. This unique orientation of polymers within the filter restricts the direction light can travel through the filter causing all light that emerges from a polarized filter to be all oriented in a single direction.

How does this work? We learned before that light behaves like a wave. As the wave of light passes through a polarized filter, the waves that move in the same orientation as the polymers in the filter get caught within the polymers and cannot pass through. The waves of light that move perpendicular to the polymers in the filter are able to snake through the polymers without getting caught and pass the filter. One way to visualize this phenomenon is by imagining a slinky. If you were to hold the slinky by one end and dangle it towards the ground, this would represent a polarized filter in the vertical position. Now, imagine moving your other hand in an up-down wave motion directly at the slinky with the goal of passing through the slinky. Your hand would get stuck in the slinky and not be able to pass through. Imagine instead that your hand is moving left to right in a wave motion trying to pass the slinky. Your hand could move around the slinky without ever touching it. This is similar to how horizontally oriented light waves can pass through a vertically oriented polarized filter. Thus, a polarized filter only allows the light in one direction to pass through it and blocks all other directions of light.

When you place a vertically oriented polarized filter (only allows horizontal light waves through) on top of a horizontally oriented polarized filter (only allows vertical light through), they actually block 100% of the light that tries to pass through the filter since each catches half of the light waves moving through the filter. There is a strange phenomenon though when you position a third polarized filter at a diagonal between the two perpendicular filters where light can start to move through the filters again. This is because the diagonal filter allows some vertical and some horizontal light waves to pass through making the beam of light you see being a mix of vertical and horizontal light waves. This mix of vertical and horizontal light waves is what scientists call *superposition* which is important for quantum research.

Key Vocabulary

Polarized filters	Polarized filters are composed of long molecules aligned in one direction. When light is shown through a polarized filter, only waves of light traveling perpendicular to the orientation of the filter molecules can pass through thus making any light that emerges on the other side of the filter unidirectional.
Resonance	This is a phenomenon where an external force (light from laser) causes another system (polarized filter) to vibrate in motion. The energy is transmitted to the second system and absorbed.
Superposition	Is a concept in quantum mechanics where something holds two values at once. For example, a coin flipping through the air is both heads and tails at the same time (at least until it lands). In the case of this activity, light is put into a superposition when a third filter is added allowing both vertical and horizontal waves of light through at the same time.

Quantum Laser Explorations

Activity #1 | Activity #2 | Activity #3 | Activity #4 | Activity #5

Engage

1. Ask students to recall what they learned about light in the previous activity.
   a. Prompting questions may be: "How does light behave?" "How do we get different colors of light?"

2. Introduce the activity: Today, our goal is to explore a phenomenon about light interacting with materials.

What is a Polarized Filter?

3. Hand out a *single* polarized filter without naming it as such (you can refer to it as a "special material") and a "Polarized Filter Observations" worksheet to each student. Ask students to explore how the material changes light within the room and record their observations when they hold up their filter to a light source (window, light bulb, projector screen, etc.). Encourage students to try multiple light sources and draw what is happening on their worksheets.
   a. After several minutes of observations, ask several students to share out their observations. Student responses may be "the light gets blocked through the filter" "some light goes around the filter" or "the filter makes the light darker"
4. Ask students what this material might be used for and elicit student ideas. Encourage students to expand on why they think the material could be used in this way.

Quantum Laser Explorations

Activity #1 | Activity #2 | Activity #3 | Activity #4 | Activity #5

Two Polarized Filters

1. Ask students to turn to a partner and explore what happens to the same light sources when they layer the two filters on top of each other. Encourage students to change the orientation of the filters.
    a. Ask students to record their observations on the worksheet.
    b. Ask students to share out their observations. If some students still have not seen the phenomenon, encourage them to try it and demonstrate for the class.
2. Using think-pair-share, ask students to form a hypothesis for what they think is happening that causes the filters to block all light when oriented perpendicular to each other.
    a. If possible, when sharing out to the class, ask students to consider how they might test their hypothesis and encourage them to do a quick test.

3. Show students the model image of a polarized filter (Slide 1). Note that a polarized filter has all the molecules that make it up (which could be polymers or metal) lined up in a single direction.
    a. Ask students to consider how they might change their hypothesis or use this image to support their hypothesis.
    b. Possible question: Knowing that polarized filters only allow one direction of light through because they make a grid, why does two filters oriented a certain way block all light?
4. Show students the *Slinky Filter* video. This video shows that when light as a wave passes through a polarized filter, it gets caught in the molecules that are in the same up-and-down direction as the wave. Waves that are perpendicular to these molecules do not get caught and pass through easier.

Quantum Laser Explorations

Activity #1 | Activity #2 | Activity #3 | Activity #4 | Activity #5

5. Ask students to fill in the direction of the polarized filter on the bottom of their worksheets. The left filter allows vertical waves through and the right filter allows horizontal waves through.

Three Polarized Filters

6. Ask students to consider what will happen when they add a third filter.

7. Hand out a *third* polarized filter to each pair and ask students to try to make the light even darker. Encourage them to start orienting the two filters perpendicular to each other so they block the light then add the third filter. **Emphasize that the third filter must be added in between the first and second like a sandwich.**
    a. Make sure to encourage students to rotate the third filter slowly and see what happens. If they have a hard time seeing through the filters, have them try to read a sign in the classroom through the filters to encourage looking *through* the filter.
    b. After several minutes of observations, ask several students to share out their observations. Student responses may be "when in the middle I could see through it when it was diagonal"
    c. Highlight the observation that when a third filter is placed diagonally between two perpendicular filters, you can now see through the dark spot again (see Slide 2 for orientation of filters).
    d. Ask students to use their knowledge of polarized filters and light to explain why this happens. Have them draw their explanations on the worksheet.

Quantum Laser Explorations

Activity #1 | **Activity #2** | Activity #3 | Activity #4 | Activity #5

8. Explain that the first filter forces the light into one direction while the second diagonal filters forces the light into a diagonal direction so it can pass through the third filter that's perpendicular to the first. This is a phenomenon that quantum scientists use to control light in their experiments.

Why does this matter?

9. Polarized filters are used in a variety of ways, let's learn how. Show the *Quantum Application: Polarized Filers and Superposition* Video to the class.

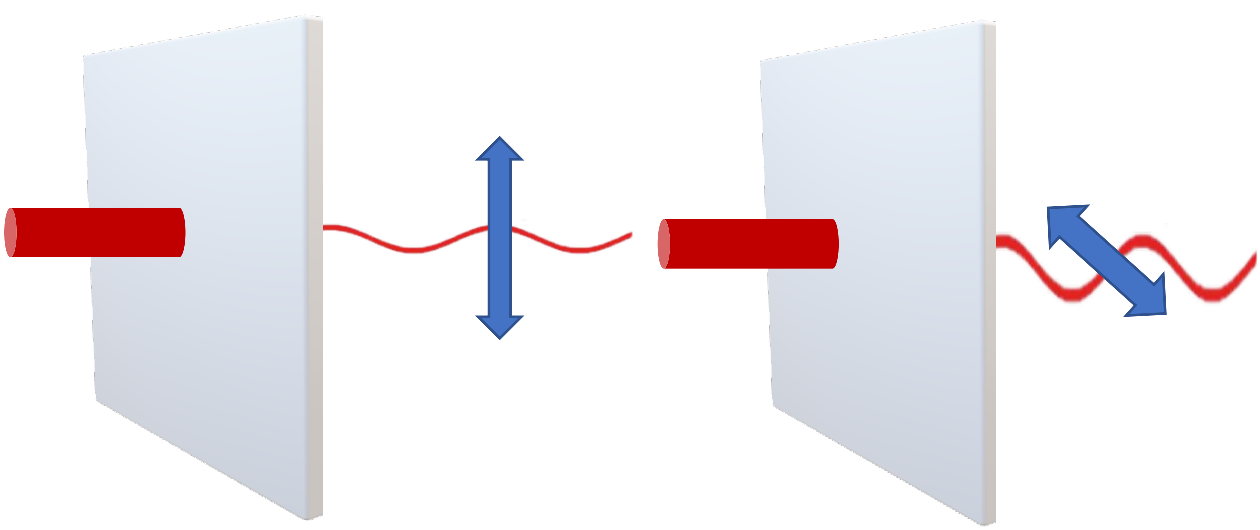
Name: ______________________________ **Date:** __________________

Polarized Filter Observations

Test 1: Hold up a single polarized filter to a light source and try to look through it. Record your observations here.

How do polarized filters work video

After watching the video explaining polarized filters, draw the direction of the filter molecules based on the direction of the wave that passes through the filter. (Hint: remember the light waves that pass through are perpendicular to the molecules in the filter)



Test 2: Hold up two polarized filters to a light source and try to look through it. Record your observations here. Try changing the way the filters are layered, does that change anything?

Test 3: Hold up two polarized filters to a light source perpendicular to each other so no light comes through. Slip a third filter in between at a diagonal and record your observations here. (Hint: only place the 3rd filter halfway through the two perpendicular filters and compare the two sections.)

Why do you think a third filter placed diagonally between two polarized filters allows some light through when just two filters didn't allow any light through?

Quantum Laser Explorations

Activity #3- Diffraction Patterns

50 min

Students learn about how light from a laser pointer creates a diffraction pattern when it passes across a small object such as a strand of hair. This diffraction pattern is caused by the interference of waves of light and can be used to measure the size of small objects.

Learning Goals
Students will understand that light travels in a straight line except at surfaces between different materials where the light path bends.
Students will understand that two light waves interfere with each other to create a diffraction pattern.
Students will use this diffraction pattern to measure the width of an object.
Students will understand how quantum scientists use this phenomenon.

NGSS Connections		
MS-PS4-2. Develop and use a model to describe that waves are reflected, absorbed, or transmitted through various materials.		
Science and Engineering Practices	**Disciplinary Core Ideas**	**Crosscutting Concepts**
Developing and Using Models to describe a phenomenon	**PS4.B: Electromagnetic Radiation** - The path that light travels can be traced as straight lines, except at surfaces between different materials where the light path bends.	**Structure and Function** - Structures can be designed to serve particular functions by taking into account properties of different materials, and how materials can be shaped and used.

Materials	
For Teacher Demonstration	**For Student Activity**
Laser pointer (red or green)	<u>*Width of a Hair Worksheet*</u> (1 per student)
1 Hair frame (see preparation for how to make)	Tray or container (per group) prepared with: - 2 laser pointers (red or green) - **Empty** hair frames (1 per student) - 1 Meter/yard stick
Lesson Videos	
Instructional PowerPoint (optional)	

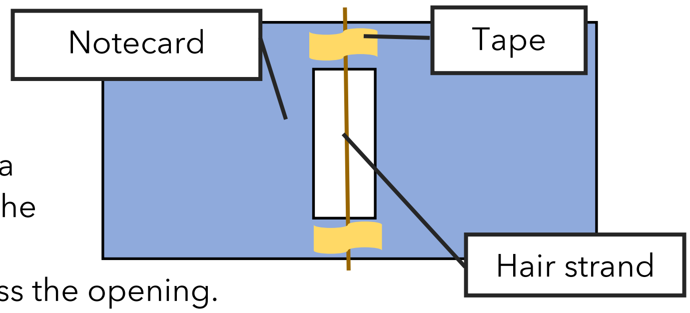
	Tape Scissors

Quantum Laser Explorations

Activity #1 | Activity #2 | Activity #3 | Activity #4 | Activity #5

Activity Preparation

1. Create Hair Frame for Demonstration
    a. To create these, you will need: Tape, a 3″ x 5″ notecard, a strand of hair.
    b. Take a 3″ x 5″ notecard and cut a hole approximately 1.5″ x 1″ in the center.
    c. Tape a piece of hair tightly across the opening. Loose hairs will not work, make sure it is as taut as possible.



2. Create Empty Hair Frames for students (optional)
    a. To create these, you will need: Tape, a 3″ x 5″ notecard, a strand of hair.
    b. Take a 3″ x 5″ notecard and cut a hole approximately 1.5″ x 1″ in the center.

3. Print *Width of a Hair* worksheets

4. Tape blank white sheets of paper around the room as stations for each group. Large white sticky notes or butcher paper works best; however, normal printer paper works as well.

5. Download or buffer the *Diffraction Patterns* and *Quantum Applications: Diffraction Patterns* videos

Quantum Laser Explorations

Activity #1 | Activity #2 | **Activity #3** | Activity #4 | Activity #5

Background Knowledge

In the first activity, we learned how light sometimes behaves like a wave, with peaks and troughs. This wave-like motion of light results in interesting behaviors when light interacts with other materials. In this second activity, we will explore what happens when a beam of light interacts with a thin object, such as a piece of hair. If you were to place a taut strand of hair in front of the laser beam, you would see the beam of light spread out into a light-dark-light-dark pattern on the wall. This is called a *diffraction* pattern. This pattern is created as the waves of light from the laser bend around the strand of hair. Some light bends to the right of the hair strand and some light bends to the left of the hair strand causing two circular wave patterns like ripples in a pond. As the two circular wave patterns of the laser beam light move past the hair, they interact with each other to create the diffraction pattern in what scientists refer to as *interference*. When the peaks of one wave meets (or interferes) with the peaks of the other wave, they combine to make a larger wave peak. The same is true when a trough in one wave meets the trough of the other wave. However, when a peak from one wave and a trough from the other interfere with each other, they cancel out which causes the dark spots you see on the diffraction pattern. We can use this diffraction pattern to calculate the width or thickness of the hair strand similar to how physicists use lasers and diffraction patterns to measure the size of particles and explore fundamental quantum mechanical concepts such as wave-particle duality.

Key Vocabulary

Diffraction	When a light wave encounters an object, it bends around the corners of the object or through an aperture. This bending of light is called diffraction.
Interference	This is when two waves interact to form a wave together that is of either lower, higher, or similar amplitude (height).

Quantum Laser Explorations

Activity #1 | Activity #2 | **Activity #3** | Activity #4 | Activity #5

Engage

1. Ask students to recall what they have learned about light and lasers so far. Emphasize the following key points:
   b. Light behaves as a wave.
   c. When light meets a material, it can be absorbed, reflected, or transmitted.

2. **Demonstrate the focus phenomenon for today.** Hold up a frame with a hair taped tightly across the opening. Shine a laser pointer at the wall making sure to hit the hair. You should see a scatter pattern.

3. Ask students to make observations about this pattern. Prompt students to form preliminary explanations as to why the laser pointer makes a certain pattern when it hits the hair.

Science Introduction

1. Show Diffraction Pattern video. Ask students to fill out questions on *Width of a Hair* worksheet.

Quantum Laser Explorations

Activity #1 | Activity #2 | **Activity #3** | Activity #4 | Activity #5

Measurement activity

1. Introduce the activity: Diffraction patterns can be used to measure the width of small objects such as human hair. Today students will measure the width of their own hair.

2. Hand out materials to students
    a. Empty hair frames
    b. Tape
    c. Scissors

3. Instruct students to create their hair frame using the following steps:
    a. Take a human hair (always ask permission before pulling someone else's hair). Make sure it is long enough to tape at both ends of your smaller inside rectangle.
    b. Tape the hair, as tight as you can, at the top and bottom of your frame so that the hair runs through the middle of the inside cutout. Your final hair frame should look like this:

Quantum Laser Explorations

Activity #1 | Activity #2 | Activity #3 | Activity #4 | Activity #5

4. Using the "Width of a Hair" slide deck, show students how to measure the width of their hair. Students should:
   a. Have one person stand approximately a meter (3 feet) away from the blank wall with the paper taped to it.
   b. That person should hold up the frame with the hair and shine the laser pointer at the paper on the wall, making sure to hit the hair with the laser beam. They should see the light scatter to the sides as they hit the hair with the laser pointer. They may need to move towards or away from the wall depending on your laser pointer to get a clear diffraction pattern.
   c. Have second person mark the center dot and the first major "dark" section to either the right or left. Measure the distance between these two marks in centimeters.
   d. Have a third person measure the distance from the hair to the paper on the wall. This is best measured in centimeters.
   e. Check the wavelength of the light produced by the laser pointer. A red laser will be about 650 nanometers, and a green laser will be about 532 nanometers. This can normally be found on the laser pointer itself.

5. Prompt students to write their measurements down on their worksheets.

Quantum Laser Explorations

Activity #1 | Activity #2 | Activity #3 | Activity #4 | Activity #5

6. Once students have all their measurements, prompt them to use this calculator, plug in the distance from the wall (cm), distance between the center dot and dark section on the diffraction pattern (cm), and the wavelength of the laser to calculate the width of the hair. Make sure you use the correct units of measurement on the calculator.
    a. Full URL: https://www.omnicalculator.com/physics/hair-diffraction
    b. Note that hair widths are normally between 17-180 micrometers. If students report findings outside of this range, encourage them to repeat their measurements.

7. Ask students to compare their hair widths. Can they identify any trends? After some discussion, share the following facts for consideration:
    a. Blonde hair is often the thinnest hair because it lacks a middle layer (called the Cortex) while black hair is the thickest.
    b. Genetics also play a role in thickness of hair with the average European hair width being about 70 micrometers while Asian hair is on average 100 micrometers wide.
    c. The hair width can also differ based on where on the head it was collected.

Connection to the Quantum Foundry

8. Explain that quantum scientists also use lasers to measure small objects which they will learn more about from XXX person, a researcher at UCSB's Quantum Foundry. Share the *Quantum Applications: Diffraction Patterns* video.

Name: ______________________________ **Date:** ____________________

Width of a Hair

Fill out the following questions while watching the "Diffraction Patterns" Video.

1. What causes the dark spots in the diffraction pattern?

2. Why can we use water to model light?

3. How is a double slit experiment similar to our hair measurement experiment? We don't have two slits.

4. In your own words, define interference.

Measure the width of your hair.

1. Fill out the table (Note: make sure to use the correct units of measurement)

Distance from hair to wall (cm)	Distance from center dot to first dark spot (cm)	Wavelength of laser pointer (nm)

2. Input values into the calculator: https://www.omnicalculator.com/physics/hair-diffraction

3. What is the width of your hair?

The average hair width is 17-180 micrometers. Does your measurement fall within this range? If not, consider why and maybe repeat your measurements.

Name: ________Answer Key__________________ **Date:** ______________________

Width of a Hair

Fill out the following questions while watching the "Diffraction Patterns" Video.

1. What causes the dark spots in the diffraction pattern?

The *interference* between multiple waves of light cancelling each other out to create dark spots.

2. Why can we use water to model light?

Water and light both behave as waves.

3. How is a double slit experiment similar to our hair measurement experiment? We don't have two slits.

The hair splits the laser beam into two separate beams whereas the double split experiments allows two separate beams to pass through.

4. In your own words, define interference.

Interference is when two waves a interact to form a wave of greater, lower, or similar amplitude (height).

Measure the width of your hair.

1. Fill out the table (Note: make sure to use the correct units of measurement)

Distance from hair to wall (cm)	Distance from center dot to first dark spot (cm)	Wavelength of laser pointer (nm)

2. Input values into the calculator: https://www.omnicalculator.com/physics/hair-diffraction

3. What is the width of your hair?

The average hair width is 17-180 micrometers. Does your measurement fall within this range? If not, consider why and maybe repeat your measurements.

Quantum Laser Explorations

Activity #4- Aperture Diffraction

50 min

Students learn about how laser pointers create a circular diffraction pattern when the beam passes through an aperture, or hole, smaller than the laser beam. Students explore how a smaller aperture results in a larger diffraction pattern.

Learning Goals
Students will understand how a diffraction pattern can be created when a laser beam is passed through an aperture.
Students will understand that a smaller aperture results in a larger diffraction pattern.
Students will understand that quantum scientists can only measure one aspect of a quantum object at a time.

NGSS Connections		
MS-PS4-2. Develop and use a model to describe that waves are reflected, absorbed, or transmitted through various materials.		
Science and Engineering Practices	**Disciplinary Core Ideas**	**Crosscutting Concepts**
Developing and Using Models to describe a phenomenon	**PS4.B: Electromagnetic Radiation** • The path that light travels can be traced as straight lines, except at surfaces between different materials where the light path bends.	**Structure and Function** • Structures can be designed to serve particular functions by taking into account properties of different materials, and how materials can be shaped and used.

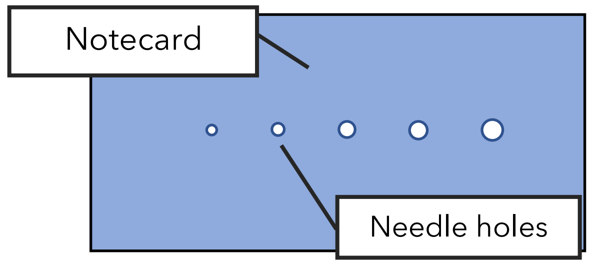
Materials	
For Teacher Demonstration	**For Student Activity**
Laser pointer (red or green)	*Aperture Diffraction Worksheet* (1 per student)
1 Aperture card (see preparation for how to make)	Tray or container (per group) prepared with: • 2 laser pointers (red or green) • 2 aperture cards • Ruler
Lesson Videos	

Quantum Laser Explorations

Activity #1 | Activity #2 | Activity #3 | **Activity #4** | Activity #5

Activity Preparation

1. Create Aperture Cards
   a. To create these, you will need: 3-4 sewing needles of various sizes, a 3" x 5" notecard.
   b. Using the smallest sewing needle, carefully create a hole in a 3" x 5" notecard by gently pushing the needle through. Try to not wiggle the needle too much as you want a clean circular hole.
   c. Using sewing needles of various sizes, create 2-4 more holes at least .25 inches away from the initial hole in order from smallest to largest diameter of needle. *Make sure the largest hole is still smaller than the beam from the laser pointer.*



2. Print *Aperture Diffraction* worksheets

3. Download or buffer the *Aperture Diffraction* and *Quantum Applications: Apertures and Measurement* videos

Quantum Laser Explorations

Activity #1 | Activity #2 | Activity #3 | **Activity #4** | Activity #5

Background Knowledge

In the last activity, we learned that as you shine light at an object, the light bends around the object to create a diffraction pattern. Previously we looked at how light bends around a straight object (a hair strand), but in this activity students investigate how light bends around a curved edge. An *aperture* or small hole has rounded edges that create the circular shape of the aperture. When light passes through an aperture, all the light waves that pass the edge bend to create a diffraction pattern similar to what was seen in the last activity; however, since the light bends at a different angle at ever part of the curved edge of the aperture, rather than getting a straight-line diffraction pattern, the diffraction pattern is in a fuzzy circular shape.

What is unique about these diffraction patterns is that the larger the aperture, the smaller the diffraction pattern and vice versa. This is because the larger aperture has more space for the light to pass through the middle without interacting with the edges of the aperture and bending the light. A smaller aperture has less space to pass through and thus more waves of light interact with the edge of the aperture and bend. This increase in bending of the light waves causes a larger diffraction pattern to appear on the wall. This phenomenon is important for scientists to understand when measuring small particle movement through an aperture.

Key Vocabulary

Aperture	This is a term used in optics to refer to the maximum diameter a hole a light beam may pass through. In this activity, the holes made in the notecards are apertures of various sizes.
Diffraction	When a light wave encounters an object, it bends around the corners of the object or through an aperture. This bending of light is called diffraction.
Measurement	This is the testing of a system to yield a numerical result. In quantum mechanics, we can only measure one aspect of a system accurately.

Quantum Laser Explorations

Activity #1 | Activity #2 | Activity #3 | **Activity #4** | Activity #5

<u>Engage</u>

1. Ask students to recall what they learned about light in the previous activity.
    a. Prompting questions may be: "How does light behave when it passes across a strand of hair?" "What is a *diffraction pattern?"* "What were we able to determine from this *diffraction* pattern?"

2. Introduce the activity: Today, our goal is to learn more about how the laser changed as it passed through a small aperture or hole.
    a. Demonstrate this phenomenon by holding up an aperture card and shining a laser beam through a single hole at the wall. Ask students to make observations and share them with the class.

<u>Science Background</u>

1. This phenomenon also is about **diffraction.** Ask students if they have any predictions, based on what they learned about diffraction in the last activity, why the diffraction pattern this time looks like a circle rather than a straight line.
    a. Possible student ideas may be "the laser is passing through a round hole rather than a straight hair so it will diffract in a circle", "the interference is happening at all points on the hole so we are seeing a bunch of line diffraction patterns that make up the circle"

2. Hand out the <u>*Aperture Diffraction*</u> worksheet and show students the *Aperture Diffraction* video. Prompt students to fill out the video questions on the worksheet while they watch.

Quantum Laser Explorations

Activity #1 | Activity #2 | Activity #3 | **Activity #4** | Activity #5

<u>Activity</u>

1. Restate the question for today: How does a diffraction pattern of a laser change when you shine the beam through different sized apertures or holes?

2. Hand out materials to groups of students
    b. Blank piece of paper
    c. Note card with 3 different sized holes pushed into them
    d. Laser pointers
    e. Rulers or yard/meter sticks
3. Using the "Width of a Hair" slide deck, show students how to measure the width of their hair. Students should:
    a. Tape the piece of paper onto a blank wall at approximately shoulder height.
    b. Turn the lights off and one person should stand approximately a meter (3 feet) away from the blank wall with the paper taped to it.
    c. That same person should hold up the frame with the holes and shine the laser pointer through the largest aperture. Students should see the light scatter in a large circle on the wall. They may need to move towards or away from the wall depending on your laser pointer to get a clear diffraction pattern.
    d. Another student should measure the diameter (width) of the diffraction pattern from edge to edge, trying to pass through the center of the circle and record the diffraction width on the worksheet.

3. Repeat this process with the rest of the holes making sure to keep the distance from the wall constant.

Quantum Laser Explorations

Activity #1 | Activity #2 | Activity #3 | **Activity #4** | Activity #5

Discussion

1. Ask students to share out their results. Which aperture made the largest diffraction pattern? Which the smallest?

2. Ask students to use their understanding of a laser passing through an aperture to form an explanation for their results. Prompt students to write their ideas on their worksheets.

Connection to the Quantum Foundry

1. Quantum scientists also use concepts that we learned today to do their work. Let's hear from a researcher at UCSB's Quantum Foundry about why this diffraction phenomenon is important to their researcher. Show the *Quantum Applications- Apertures and Measurement* video.

Name: ________________________________ **Date:** ___________________

Aperture Diffraction

Fill out the following questions while watching the "Aperture Diffraction" Video.

1. Why does the diffraction pattern when shining a laser through an aperture look different than when shining the laser at a strand of hair?

2. Why is the diffraction pattern fuzzier than the hair diffraction pattern that was a straight line?

Question of Activity: How does a diffraction pattern of a laser change when you shine the beam through different sized apertures or holes?

1. Shine a laser beam through various sized apertures (holes) and measure the diameter of the diffraction pattern. Record your measurements below:

Aperture size	Diameter of Diffraction Pattern (cm)
Smallest	
Largest	

2. What trends do you see in your data?

3. Why do you think this trend emerged? Write or draw a potential explanation for your results.

Name: _______**Answer Key**____________________ **Date:** ________________________

Aperture Diffraction

Fill out the following questions while watching the "Aperture Diffraction" Video.

1. Why does the diffraction pattern when shining a laser through an aperture look different than when shining the laser at a strand of hair?

Diffraction is the bending of light around the corner of an object the light encounters. When shining a laser at a strand of hair, the "corners" of the hair are positioned in one direction, so the bending of light happens in one direction resulting in the linear diffraction pattern. When a laser is shone at a circular aperture, the light bends around the entire circumference of the circle causing a circular diffraction pattern.

2. Why is the diffraction pattern fuzzier than the hair diffraction pattern that was a straight line?

As the light bends around the entire circumference of the circular aperture, it's creating many linear diffraction patterns which result in a "fuzzy" pattern that we see in the shape of a circle.

Question of Activity: How does a diffraction pattern of a laser change when you shine the beam through different sized apertures or holes?

1. Shine a laser beam through various sized apertures (holes) and measure the diameter of the diffraction pattern. Record your measurements below:

Aperture size	Diameter of Diffraction Pattern (cm)
Smallest	
Largest	

2. What trends do you see in your data?

The smallest aperture creates a larger diffraction pattern.

The largest aperture creates a smaller diffraction pattern.

3. Why do you think this trend emerged? Write or draw a potential explanation for your results.
   Answers will vary.

Quantum Laser Explorations

Activity #5- Final Reflections

50 min

Students reflect upon the previous four lessons and work to explain the phenomenon used in their initial art pieces created in Activity #1.

Learning Goals
Students will demonstrate an understanding of how lasers behave under three different conditions.
Students will demonstrate an understanding of how the phenomenon and concepts explored in this unit connect to quantum research.

<table>
<tr><th colspan="3">NGSS Connections</th></tr>
<tr><td colspan="3">MS-PS4-1. Use mathematical representations to describe a simple model for waves that includes how the amplitude of a wave is related to the energy in a wave.
MS-PS4-2. Develop and use a model to describe that waves are reflected, absorbed, or transmitted through various materials.</td></tr>
<tr><th>Science and Engineering Practices</th><th>Disciplinary Core Ideas</th><th>Crosscutting Concepts</th></tr>
<tr><td>Developing and Using Models to describe a phenomenon</td><td>PS4.B: Electromagnetic Radiation
- Waves are reflected, absorbed, or transmitted through various materials</td><td>Structure and Function
- Structures can be designed to serve particular functions by taking into account properties of different materials, and how materials can be shaped and used.</td></tr>
</table>

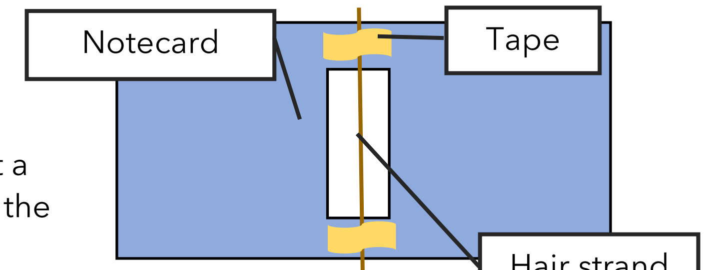
Materials
Art pieces from Activity #1
Quantum Art Captions Worksheet (1 per student)
Tray or container (per group) prepared with: - 2 laser pointers (red or green) - 2 polarized filters - 2 aperture cards - 2 Hair frames - Photo capturing device (i.e., iPad or computer)

Quantum Laser Explorations

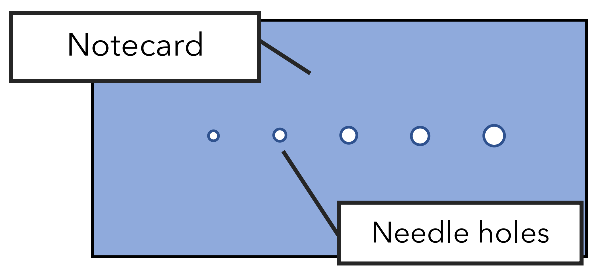
Activity #1 | Activity #2 | Activity #3 | Activity #4 | Activity #5

Activity Preparation

1. Create Hair Frames
    d. To create these, you will need: Tape, a 3″ x 5″ notecard, a strand of hair.
    e. Take a 3″ x 5″ notecard and cut a hole approximately 1.5″ x 1″ in the center.
    f. Tape a piece of hair tightly across the opening. Loose hairs will not work, make sure it is as taut as possible.
    g. If you are uncomfortable preparing these slides for students, hand them pre-cut notecards and have them tape their own hairs across the openings.



2. Create Aperture Cards
    a. To create these, you will need: 3-4 sewing needles of various sizes, a 3″ x 5″ notecard.
    b. Using the smallest sewing needle, carefully create a hole in a 3″ x 5″ notecard by gently pushing the needle through. Try to not wiggle the needle too much as you want a clean circular hole.
    c. Using sewing needles of various sizes, create 2-4 more holes at least .25 inches away from the initial hole in order from smallest to largest diameter of needle. Make sure the largest hole is still smaller than the beam from the laser pointer.



3. Print _Quantum Art Captions_ worksheets.

4. Download or buffer the _Careers in Quantum_ video.

Quantum Laser Explorations

Activity #1 | Activity #2 | Activity #3 | Activity #4 | Activity #5

Background Knowledge

Lasers, while commonly found at concerts and as toys to tease your cat, are extremely useful in the world of *quantum mechanics* as a tool to measure small objects and understand quantum properties. Light travels as a wave with different colors of light having different wavelengths. For example, wavelengths of about 400nm create a purple light while wavelengths of 700nm create red light. When a flashlight is shone, light of all wavelengths is produced which creates the white beam of light. Lasers are unique in that they emit light of similar wavelengths that travel together with peaks and valleys of the wave lined up, or what scientists call *in phase*. This causes a very narrow and bright beam of light to be produced when a laser pointer is shined at a wall. The *in phase* nature of laser beams allows for unique phenomenon to occur when the laser beam interacts with other materials such as an aperture, polarized filter, or strand of hair. These unique behaviors of light are not only beautiful, but also allow scientists to use lasers to measure small objects and create efficient and accurate communication devices.

Key Vocabulary

Polarized Filter	Polarized filters are composed of long molecules aligned in one direction. When light is shown through a polarized filter, only waves of light traveling perpendicular to the orientation of the filter molecules can pass through thus making any light that emerges on the other side of the filter unidirectional.
Diffraction	When a light wave encounters an object, it bends around the corners of the object or through an aperture. This bending of light is called diffraction.
Interference	This is when two waves interact to form a wave together that is of either lower, higher, or similar amplitude (height).
Aperture	This is a term used in optics to refer to the maximum diameter a hole a light beam may pass through. In this activity, the holes made in the notecards are apertures of various sizes.
Quantum Mechanics	A theory in physics that describes the nature of atoms and sub-atomic particles. It is the foundation of all quantum sciences.

Quantum Laser Explorations

Activity #1 | Activity #2 | Activity #3 | Activity #4 | Activity #5

Engage

1. Ask students to reflect upon the last three activities:
    a. Polarized filters- what is a polarized filter? How did it change the laser beam?
    b. Width of a hair using diffraction- What happened when we shone a laser beam at a piece of hair? Why did this happen?
    c. Diffraction through an aperture/hole- What happened when we shone a laser beam through a small aperture? Why did this happen? What happened when we changed the size of the aperture?

Revisit Art Pieces

1. Regroup students into the original art groups at the beginning of this module. Ask students to revisit the art pieces they made together and prompt them to recreate their art piece. If they want, they can redesign their art piece using new techniques they have learned over the past three lessons.

2. Hand out materials to each group of students. Each group should receive:
    a. Two laser pointers
    b. Two polarized filters
    c. Two string frames
    d. Two aperture cards
    e. Photo capturing device (i.e., iPad or computer)

3. Allow students 5-10 minutes to recreate and/or redesign their art piece. If students seem stuck, encourage them to make multiple designs, layer different techniques, play with the camera settings, etc.

Quantum Laser Explorations

Activity #1 | Activity #2 | Activity #3 | Activity #4 | **Activity #5**

Caption Writing

1. Now that they have a finalized piece of laser-art, students will write a caption to describe (1) the technique used to make the art (2) the science behind the art that explains the phenomenon and (3) at least one connection to how scientists use one phenomenon at the Quantum Foundry.

2. Hand out the *Quantum Art Captions* worksheet to each group and allow them 15 minutes to write their captions together. Encourage them to define any vocabulary they might use in their captions.

Wrap-up

1. Emphasize that quantum scientists use the techniques and phenomenon that students learned about in this module. There are lots of interesting careers studying lasers or quantum physics that students could pursue. Show the *Careers in Quantum* video to students.

Name: ____________________________________ **Date:** _____________________

Quantum Art Captions

In art displays, there are often placards next to the art piece that describes the piece. Write a caption that describes (1) the technique used to make the art (2) the science behind the art that explains the phenomenon and (3) at least one connection to how scientists use one phenomenon at the Quantum Foundry.

To make this art piece, I ____

____

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This patterns happens because ____

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This connects to the UCSB Quantum Foundry because ______________________

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