Quantum Measurement

Thrust 2: Interfaced Topological States

7th - 8th Grade

Version 2. 08/28/2023

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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 Measurement Storyline

When adapting these activities for a classroom environment, the following storyline can help you connect the individual activities together. Consider providing a reflection activity at the end of the three activities asking students to share how scientists measure and interact with unseen objects and how that helps with quantum sciences.

Activity #1 Quantum Sensing	**Lesson Question**
	How do we learn about the properties of objects which we can't see? By watching or listening closely to how an object responds, what can we learn about it?
	Phenomena
	When sound passes through different shaped objects, the resonant frequencies of the objects cause the pitch to alter. This pitch can be used to help measure an object with an unknown shape.
	What We Do and Figure Out
	Students will learn that an object will respond to sound depending on its physical dimensions, and that the response can be used to learn about an object which cannot be directly measured.
	Connection to the Quantum Foundry
	Atom-like systems (atoms/ions, NV centers, quantum dots, etc) are interrogated by driving them with light of various frequencies. By observing their response -- which frequencies are reflected, for instance -- one can learn about the structure of these systems.

Navigation: Now that students have learned a bit about how unknown objects can be measured using sound, they will investigate how other unseen forces can be used to measure objects.

Activity #2 Magnetic Resonance	**Lesson Question**
	How can we use magnetism and electricity to measure the properties of an object? How do these to forces interact?
	Phenomena
	Compasses are sensitive to magnetic fields and can be used to map the direction of magnetic fields and uncover the location of objects hidden to the naked eye. Compasses can also be used to map the direction of the magnetic field produced by an electric current.
	What We Do and Figure Out
	Different objects (atoms, compasses, tubes) are sensitive to and resonate due to different forces around them. If we can find the right object (in this case a compass) and calibrate its resonances, we can measure the strength and frequency of all kinds of different forces/fields around us.

	Quantum sensing is doing this at a very small scale where quantum mechanics tells us what forces guide our compass behavior.
	Connection to the Quantum Foundry
	Quantum sensing involves exactly this same experiment, except atoms in a crystal act as our tiny compass. Using atoms, we can map out even the smallest changes in magnetic fields that a regular compass wouldn't be sensitive enough to detect, because it wouldn't be able to oscillate as fast as the fields we are trying to detect (millions/billions of times a second!).

Navigation: Students have learned how some objects are affected by invisible fields and that scientists can use these interactions to determine the physical properties of the unseen. Next they investigate how scientists can photograph objects that are not easily seen.

Activity #3 Imaging with Shadows	**Lesson Question**
	How do we take pictures of objects at the quantum scale, which don't reflect or emit light the way larger objects do?
	Phenomena
	By using lenses placed apart from each other, we can magnify an object that the eye cannot see enough to photograph it.
	What We Do and Figure Out
	Students learn about modern imaging and optics techniques by constructing an imaging telescope. Students will align a laser pointer through 2 lenses and a small object and try to construct an image of that object at the image plane. Through this activity students will learn about lenses, optics alignment, and how these methods tie into how scientists extract data from their quantum systems.
	Connection to the Quantum Foundry
	Absorption imaging is a common technique Researchers at the Quantum Foundry use to take pictures of ultracold trapped atoms

Quantum Explorations: Measuring the Unseen

Program Cart #1: Exploring Acoustic Resonance

Target age: 8+ years

8 min

Materials

- 1 Mystery Box
  - Cardboard box with ½" diameter holes cut into the top (or any non-see through box)
  - PVC tubes of various lengths
  - PVC caps for some tubes
  - Hot glue or caulk
- White noise generator (preferably on a smartphone or tablet)
- ½" PVC: ~4" and 5" segment
- ¾" PVC: 4" segment (cut to match one of the ½" PVC segments)
- PVC caps for each segment (can also use tape)

NGSS Connections

Disciplinary Core Ideas

PS4.B: Wave Properties

PS4.C: Information Technologies

Cross Cutting Concepts

Patterns

Structure and Function

Summary

Visitors will learn about how sound waves can be used to identify various lengths of tubes. Using a white-noise generator, visitors will develop an understanding of the relationship between pitch and tube length. Based on this exploration, visitors will then sort tubes of unknown length using their white-noise generator.

Learning Goals

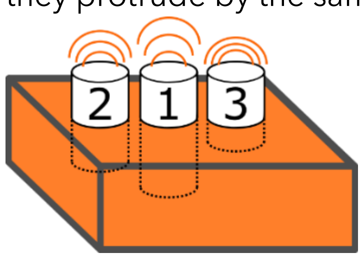
- Visitors will develop a conceptual model of resonance pitch.
- Visitors will develop a conceptual model of the relationship between resonance pitch and length of a tube.
- Visitors will develop an understanding of how sound waves can be used to measure a property of an unknown object.

Activity Facilitation

1. **Visitors observe a phenomenon.** Demonstrate how placing a the speaker of the white noise generator at the end of a PVC tube causes the white noise to change sounds. Encourage visitors to explore the different PVC tubes available to see how each tube changes the white noise sounds. Encourage them to try adding and removing caps to see how that changes the sound produced.
   a. Ask visitors if they notice any patterns in how the noise changes.
2. **Visitors develop a model.** Ask visitors why they think different length PVC tubes create different noises. Encourage them to test any testable hypotheses in their models.
3. **Provide a challenge.** Ask visitors to rank the PVC tubes in the mystery box from longest to shortest using the white noise generator and patterns they learned from exploring. Encourage the visitors to test their predictions on the known tube lengths.

Activity Preparation

1. Prepare PVC tubes
    a. Using the ½" PVC, cut two tubes to different lengths (4" and 5" work well, but shorter/longer is fine). Label the longer one "A", and the shorter one "B".
    b. Measure **one** of the ½" tubes, then cut a piece of ¾" PVC to the same length. Label it "C".
        i. These need to be pretty close – use a white noise generator like in the student activity and listen to make sure the resonance is very close for the matching ½" and ¾" tubes.
    c. Apply endcaps to all three pieces of PVC – no glue is necessary. One can alternatively use bits of tape on each tube, but care should be taken to apply the tape straight on to the end of the pipe (without stretching the tape).
2. Prepare Mystery Boxes
    a. Cut ½" PVC tubes into various heights and label them with a letter. Do not label them in order of height, your visitors will be trying to order the tubes from longest to shortest. Recommended lengths are:
        - 3" tube
        - 4" tube
        - 4" tube with a cap
        - 5" tube
        - 6" tube
        - 6" tube with a cap
    b. Cut 6 ½" diameter circles into the top of the carboard box.
    c. Push all tubes through the top of a box making sure the caps of any tubes are placed within the box and not outside. Arrange all PVC tubes so that they protrude by the same length (see diagram).



    d. To get the tubes to stay fixed at the right height, you can glue/caulk the PVC to the box lid, pack the box with bubble wrap or foam, or wrap rubber bands or tape around the tubes to stop them from falling through the holes.

Background Knowledge

Sound travels through air as vibrations of air molecules. The pitch (that is, the tone that you hear) of a sound wave is determined by its **frequency**. When sound is played into an enclosed space (a tube), some frequencies are reduced and get quieter, while others are enhanced and get louder. The frequencies which are enhanced are said to be **resonant** with the tube.

Which frequencies a given space is resonant with depends on the geometry of the space. In this exercise, visitors will discover that the resonant frequency of a tube depends only on its length. Students will be playing **white noise** into the tubes. White noise is a mixture of all the frequencies of sound that we can hear. When it enters the tube, most of the frequencies are damped out, while only a few (the resonant frequencies) are reflected strongly. This results in a distinct tone corresponding to the primary resonant frequency in the tube.

Since the length of the tube directly determines which frequencies are resonant, and thus which tones will be heard when applying white noise, visitors will be able to sort tubes by length purely based on the reflected tone!

Optional information for your own interest, or for more advanced visitors: When sound of a given frequency is played into a tube, the sound waves travel to the back of the tube, reflect off the end, then begin travelling back. The reflected wave overlaps with the incident wave, and the two overlapping waves **interfere** – adding up in some places and cancelling out in others. The way that the waves overlap, and thus how much they add up or cancel, depends on how far they travel before reflecting. For certain lengths of tubing, the waves overlap in *just* the right way as to completely add up, or **constructively interfere**. We say that a tube of this length is **resonant** with that frequency of sound wave.

Key Vocabulary

Frequency	The rate at which a wave vibrates – for sound, the air shakes back and forth.
Resonance	A powerful response of a system to a specific frequency of light, sound, etc.
White Noise	Sound composed of all frequencies (tones) in the audible range. (20 Hz – 20 kHz). This is like white light, which contains all the colors.
Interfere	What happens when waves overlap – they can add up or cancel each other.
Constructive Interference	When two waves overlap so that their peaks perfectly align, and they add up without cancellation – results in a more intense wave (louder, brighter).

Take Home Activity Modification

Visitors can make their own resonant pan flute to take home.

Additional Materials

- 3 boba straws/ visitor
- Scissors
- Masking tape

Activity Facilitation

1. After completing steps 1 and 2 of the original activity above, provide visitors with 3 boba straws and a pair of scissors.
2. Ask visitors to cut the straws into various lengths. Encourage visitors to use both sides of the straw that they cut so they have 6 short straws in total after cutting them.
3. Using what they learned in step 2 of the original activity, ask visitors to order the straws from what they think will have the lowest pitch to the highest pitch.
   a. Ask visitors why they chose that specific order, how they think the sound will differ between PVC pipes and boba straws.
4. Using the white noise generator, have visitors test their predictions and adjust accordingly.
5. Once visitors are happy with the order of their boba straws, use the masking tape to secure the straws together into a pan flute. Make sure one end of all straws are lined up before taping them together. This will make it easier to use the white noise generator on the straws later.

Classroom Adaptations

Exploring Acoustic Resonance

Additional Materials: Rulers, Worksheet (1 page)

Step 1: Demonstrate the application of the white noise generator to PVC tubes of various lengths and ask students to make observations and record them on the worksheet.

Step 2: Provide each group of 4-5 students with a set of various sized PVC tubes. Ask students to measure the length of each PVC pipe and apply a white noise generator to the end of each. Encourage students to write the lengths of each PVC tubes in order from lowest pitch to highest pitch.

As a class, discuss the patterns students observed. Ask students to consider how they could use the patterns they identify to determine the lengths of an unknown PVC length.

Step 3: Using a mystery box, ask students to observe you applying the white noise generator to each tube and record their predictions of shortest PVC tube to longest PVC tube. Encourage students to use evidence from Step 2 to support their predictions.

Quantum Connection: Share with students how this activity connects to the quantum foundry and discuss what they think some differences between this macro-scale activity and the nano-scale methods scientists use.

Exploring Acoustic Resonance Worksheet

Teacher Demonstration. Record your observations below.

Pitch versus PVC Tube Length. Record the lengths of the PVC tubes (in centimeters) provided in order from lowest pitch to highest pitch.

Lowest Pitch Highest Pitch

__________ __________ __________ __________ __________

Mystery Box Predictions. Record your predictions of PVC tube lengths from shortest to longest.

Shortest Length Longest Length

__________ __________ __________ __________ __________

Quantum Explorations: Measuring the Unseen

Program Cart #2: Sensing and Harnessing Magnetic Fields

Target age: 8+ years

20 min

Materials

- Small compasses
- Bar magnets
- Magnetic Mystery Box
- Mystery Box Worksheets
- AA Batteries
- AA Battery holder with wires connected
- Small magnets
- Wire in 6" strips

NGSS Connections

Disciplinary Core Ideas
- PS2.A: Forces and Motion
- PS2.B: Types of Interactions

Cross Cutting Concepts
- Cause and Effect
- Energy and Matter

Summary

This activity is made up of three stand-alone mini activities exploring electricity and magnetism. In the first activity, visitors use a compass to explore the magnetic fields produced by a box of unknown magnets. In the second activity, visitors use a compass to explore the magnetic fields produced by an electric current. Lastly, visitors combine magnets and electricity together to build a *homopolar battery motor*—a spinning wire motor.

Learning Goals

- Visitors will develop a conceptual model of how a compass/magnet responds to magnetic fields.
- Visitors will develop an understanding of how a compass/magnet can be used to measure electromagnetic forces and magnetic fields that cannot be directly seen.
- Students will develop an understanding of how an electric current can be used to generate magnetic fields.

Activity Preparation

3. Prepare Magnetic Mystery Boxes
   a. Using a medium sized box (e.g., a shoe box), tape or glue down several bar magnets in various positions.

b. Make sure that the top of the box can be removed easily without disturbing the magnets so visitors can check their predictions.

Activity Facilitation

Sensing Magnetic Fields with Compasses

4. Hand visitors a compass and ask them to observe how the needle behaves when they move around the space.
   a. Visitors should note that the needle points to the "N" which represents Magnetic North.
5. Ask the visitor to move the compass around the bar magnet and observe how the compass needle moves.

6. Ask them to predict how the needle would move if the bar magnet was rotated 90 degrees and test their prediction.
7. Challenge the visitor. Present the Magnetic Mystery Box and explain that there are several bar magnets placed within the box in different orientations. Challenge the visitor to draw a map of the hidden bar magnets.

Sensing Electric Fields with Compasses

1. Ask the visitor to explore how the compass needle moves when placed around a battery outside of the holder and in the holder on a complete circuit (wires are connected).
   a. Ask visitor to make predictions about why the compass moves when the battery is plugged into the closed-circuit battery holder.
2. Explain that when electricity moves, the current creates a magnetic field. Challenge the visitor to use their compass to identify the direction of the magnetic field if the current moves from the positive end of the battery to the negative.

Creating a Magnetic Motor

1. Ask visitors what will happen if you move the negative end of one magnet towards the negative end of another magnet. Encourage them to test their predictions.
   a. Visitors should find that the magnets "push" against each other.
2. Explain that we can use this magnetic push to create a spinning motor.
3. Create the spinning motor.
   a. Ask visitor to stack 4-5 small magnets and place the negative end of the battery on top of the stack so they create a mini tower.
   b. Hand visitors a 6-8" strand of wire to coil. The coil should be bigger than the battery so that it can spin around the battery. Position the coil so that one end hangs on the positive side of the battery and the other end touches the magnets at the bottom.
   c. The wire should start to spin when connected to the battery and wires. The visitor may need to adjust their wire coil to sit properly. The coil may also need a gentle nudge to start the rotation.

4. If visitors have completed the other two activities exploring magnetism and electricity, ask them to come up with an explanation of why the motor spins.
5. If visitors would like an additional challenge, provide them with a new strand of wire to create a fun shape that can spin around the magnet-battery tower.

Background Knowledge

Magnets have north and south poles. Opposite poles attract or pull towards each other while similar poles repel or push away from each other. Magnets are commonly found on fridges or in classrooms; however, the Earth is also a magnet. The way that we determine where the north and south pole of the Earth is by using a compass. Compasses have a small magnetic strip (the needle) suspended so that it can spin freely to align with the magnetic north and south poles of the Earth.

Compasses can also be used to measure the **magnetic field** of smaller magnets to determine the direction and orientation of bar magnets. When a compass is moved close to a bar magnet, the magnetic field of the bar magnet overcomes the Earth's magnetic field and pushes the compass to align with the north and south pole of the bar magnet. These types of magnets are called **permanent magnets**.

Magnetic fields can also be created by electricity flowing through current-carrying wires. **Current** is the movement of electrons which produces a magnetic field perpendicular to the movement of the electrons. Similar to permanent magnets, compasses can be used to measure the direction of the magnetic field produced by an electric current.

When electrons move within a magnetic field, they experience a force perpendicular to both the magnetic field and electron motion. This interaction is called the Lorentz force and the vertical motion of the electrons in the magnet's magnetic field causes the wire to spin about the battery.

Key Vocabulary

Magnetic field	A quantity that has a direction and a strength everywhere in space representing how strong a force a compass needle (or other magnetic object like iron filings) would feel.
Permanent magnet	An object that does not require current to produce a magnetic field.
Current	The movement of electrons, typically in a wire. Currents produce magnetic fields.
Motor	A mechanism to convert current into motion.

Magnetic Mystery Box Worksheet

Draw how you think the bar magnets are oriented within the mystery box. Check your predictions when done.

Magnetic Mystery Box Worksheet

Draw how you think the bar magnets are oriented within the mystery box. Check your predictions when done.

Classroom Adaptations

Sensing and Harnessing Magnetic Fields

Additional Materials: Worksheets (2 pages)

Step 1: Give pairs of students a compass to move around the classroom with and a bar magnet to explore with the compass. Using their observations, ask students to draw on their worksheets where the compass needle should point based on the orientation of the bar magnet. Using a camera to project onto a screen, move a magnet around a mystery box and ask students to use their observations of how the compass needle moves to map out where they think each magnet in your mystery box is. If materials are available, the mystery box can be done in small groups instead.

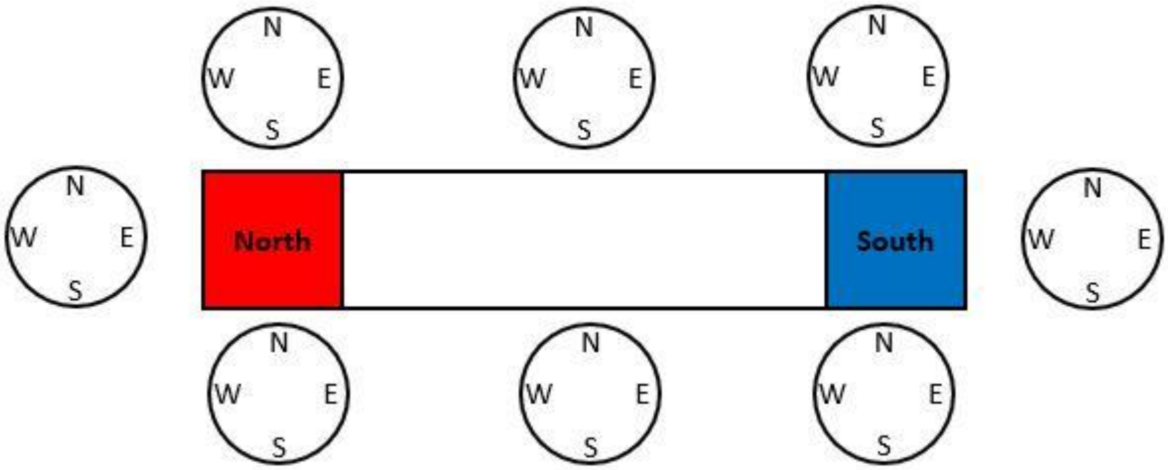
Step 2: Demonstrate the electric field generated in step 2 and ask students to record their observations. Ask students to use evidence to explain how they know a electricity produces a magnetic field.

Step 3: Provide materials to small groups of 4-5 students. Once constructed, ask students to draw a model of what they think is happening in their motor to cause the wire to spin. Encourage them to remember what happened when two magnet poles of the same type (e.g., North to North) were pushed together and where magnetic fields were found in steps 1 and 2. Ask students to share out their models.

Quantum Connection: Share with students how this activity connects to the quantum foundry and discuss what they think some differences between this macro-scale activity and the nano-scale methods scientists use.

Sensing and Harnessing Magnetic Fields Worksheet

Compass Exploration. Draw the orientation of the compass needle in the different points around the bar magnet. Make sure to label the north and south ends of the needle.



Magnetic Mystery Box. Using your observations, draw the position and orientation of the hidden bar magnets inside of the mystery box.

Electric Magnetic Field. Write or draw your observations of the demonstration.

Magnetic Motor. Draw a model of how you think the motor is spinning. Be sure to label your diagram and note any forces.

Quantum Explorations: Measuring the Unseen

Program Cart #3: Imaging Ultrafine Features

Target age: 8+ years

10 min

Materials

- 1 Optics rail
- 2 Red laser pointers
- 3 Lens mounts
- 1 3D printed laser mount
- 3 lenses of focal points:
    -
    -
    -
- Acrylic pane with mount
- Printer paper
- Clear scotch tape
- Masking tape
- Pencils

NGSS Connections

Disciplinary Core Ideas

PS2.B: Types of Interactions

PS3.C Relationship between Energy and Forces

Cross Cutting Concepts

Cause and Effect

Energy and Matter

Summary

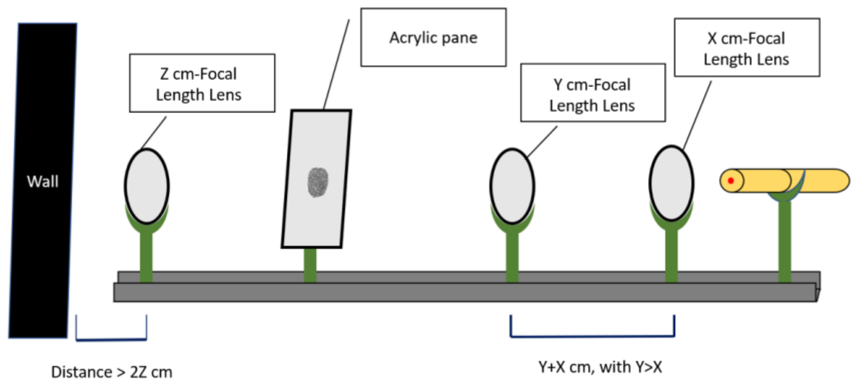
Using lenses set up on a track, visitors will explore how lenses can be used to magnify microscopic objects to be seen. Visitors will be introduced to the concept of resolution, focal and magnification, and key concepts in the optical studies of quantum systems.

Learning Goals

- Visitors will develop a conceptual model of optical magnification.
- Visitors will develop an understanding of how lasers can be used to study microscopic objects.
- Visitors will be introduced to basic optical principles.

Activity Preparation

1. Prepare the magnification rail.
    a. Set the rail on a flat surface near a wall. Make sure the acrylic pane is at least 2m distance away from the wall. The further from the wall, the larger the magnified image will be.
    b. Arrange the lenses, and acrylic pane on the rail to match the diagram below:
    c. Tape a printer paper onto the wall so that the laser will shine on it when turned on. Make sure this height is accessible for your visitors.



Activity Facilitation

Exploring Lasers and Acrylic

8. Ask visitors to take a print of their thumbs by pressing a piece of clear scotch tape onto their thumb pad, pressing firmly to ensure a clean print. Gently remove the tape and place it firmly on the acrylic pane so the laser beam passes through the imprint of their thumb when inserted on the optics rail.
    a. Tip: Mark with a sharpy where the tape should be placed to align with the laser to make it easier to place thumb prints for future visitors.
9. Ask visitors to make observations about the nature of the light emitted from the non-mounted laser pointer. Remind visitors that laser pointers are not to be pointed into anyone's eyes.
    a. Highlight visitor comments that remark on the size of the light beam emitted from the laser pointer.

b. Ask visitors to shine the laser pointer through their thumb print on the acrylic pane (without passing through any lenses) and share what they observe.

Exploring Lenses to Magnify

10. Inform visitors that light can be used to magnify an object so that we can see it better; however, we need the help of lenses to achieve this phenomenon.
11. Secure the acrylic pane on the optics rail and ask visitors to observe what happens when the laser pointer is turned on. They should notice that the light beam gets big enough to cover their thumb print, but that the pattern it makes on the wall is fuzzy.
12. Ask visitors to slide the 3rd lens back and forth until the image becomes clear. This is similar to turning the focus knob on a microscope or camera lens.
13. When visitors have created a clear image, ask them to make observations of their thumb print design.
    a. What shapes do they see in their thumb imprint?
    b. Does this look similar or different to their family members' imprints?
14. Ask them to make observations about the size of the light beam and make predictions to the role of each lens.
    a. The first two lenses magnify the size of the laser pointer beam to be able to cover the thumb print. The third lens magnifies the shadows cast by the thumb print so that we can see minute details.
    b. Explain that this is similar to how quantum scientists take measurements of microscopic objects, or objects too small for the eye to see when making materials for quantum computers to use.
15. Invite the visitor to trace their thumb imprint on the paper taped to the wall for them to take home.

Additional Challenge

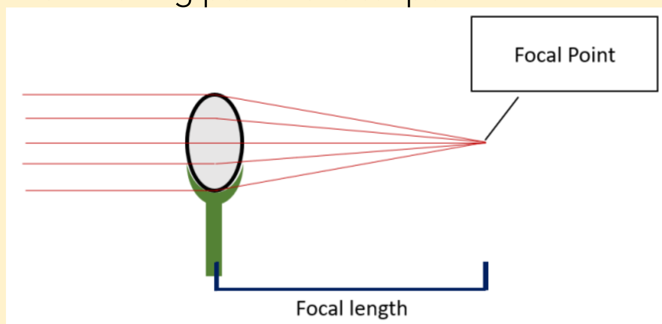
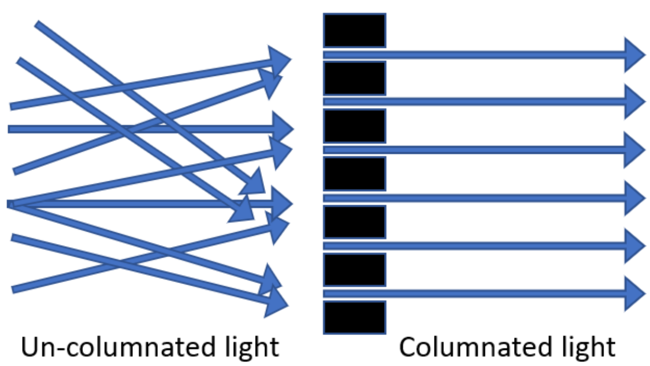
1. Invite the visitor to draw a small design on the acrylic pane using a fine-point sharpie. Use the same setup above to magnify their drawing.
2. Use isopropyl alcohol to clean the acrylic pane after use.

Background Knowledge

Lenses can be used to see objects that are too small or two far away for the naked eye to see. When light that has reflected off of an object passes through a lens, the waves of light bend to a singular point called a **focal point**. The distance between the lens and the focal point is called the **focal length**. As light moves past the focal point, the waves begin to spread back out in an inverse of the original light waves. If allowed to travel a distance greater than two focal lengths, the image will we see will be larger than the original image. This is how lenses are used to **magnify** objects. The father you allow light to travel after passing through a magnifying lens, the larger the object appears.

In this activity, light is shone from a laser pointer which has a very small light beam area, unlike a flashlight that has a very large light beam. This is because laser pointers produce **collimated light**, or light that has the peaks and valleys of light waves stacked on top of each other in sync. Because the light from the laser is so concentrated, two lenses are used to magnify the light beam to be large enough to shine on the thumb print. The first lens magnifies the light beam, while the second lens directs the light in a straight line at the thumb print on the acrylic pane. As the light shines on the acrylic pane, a shadow is cast by the thumb imprint. The light passes through a third lens to magnify the light with shadow, which reveals the shape of the thumb print. By moving the third lens, until the thumb print shadow image becomes clear, visitors are positioning the lens in the proper focal point position to capture the image of the thumb print.

Key Vocabulary

Lenses	A piece of transparent material that is used to form an image of an object by focusing light. In this we use acrylic, but glass is also a common material.
Focal point	The point at which light waves meet after having passed through a lens. Light waves converge to the focal point and diverge when moving past the focal point. 
Focal length	The distance between the center of the lens and its focal point.
Magnification	The use of lenses to enlarge the apparent (not physical) size of an object. In this activity, we enlarge the shadow an object makes.
Columnated light	Columnated light is the light produced by a laser. This is when all of the rays of light are parallel to each other, so they do not spread much when shone. 

Classroom Adaptation

Program Cart 3: Imaging Ultrafine Features

*This activity is best done as a classroom demonstration, but below are some ideas to make the activity more interactive in a classroom.

Additional Materials: For each group supply an acrylic pane, laser, and scotch tape.

Step 1: Provide students with acrylic pane, laser and scotch tape. Additionally for accessibility the optical rail can be replaced with a LEGO baseplate and the lens and laser mounts can be replaced with LEGO assemblies detailed by Junichi Takahara from Osaka University (here). Lens can also be bought from Amazon.

Step 2: Provide small groups of students with an acrylic pane, laser, and scotch tape. Following the directions in Prof. Takahara's manual, have the students assemble the LEGO lens and laser mounts.

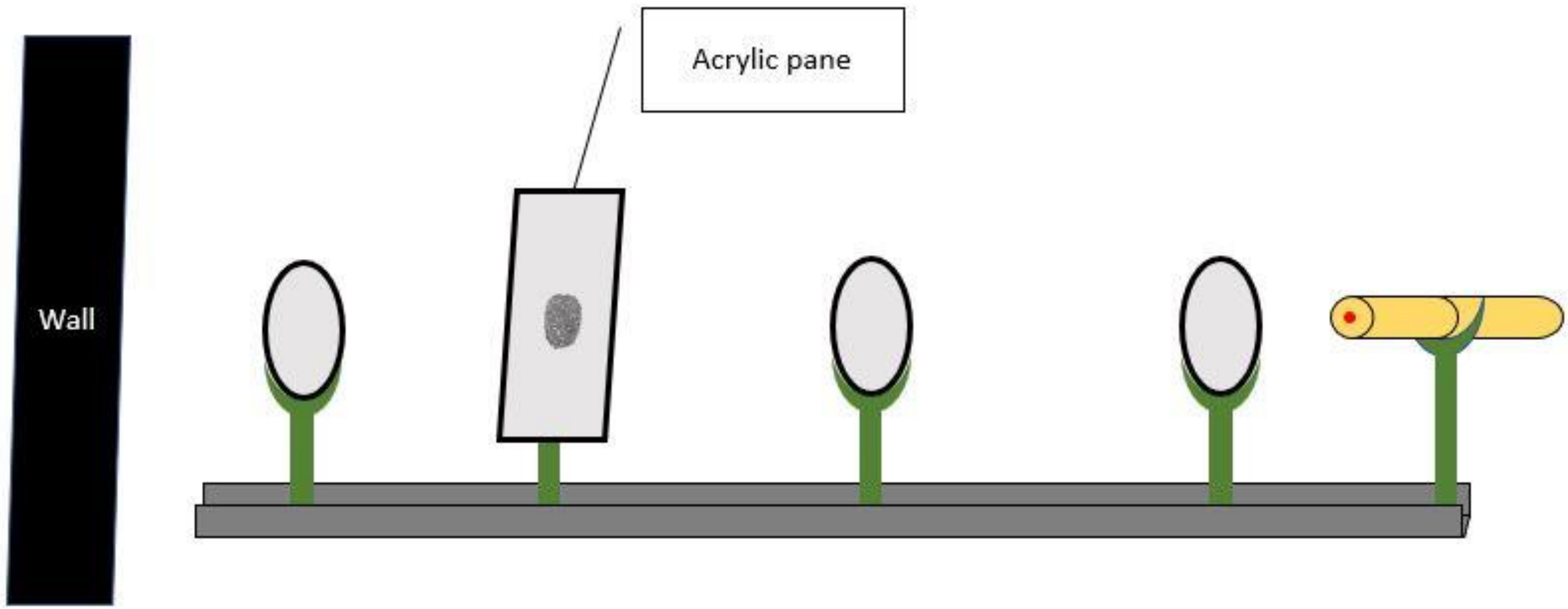
Step 3: Have the students place the laser in front of two lenses, with the longer of the two focal lengths mounted after the shorter of the two, mounted collinearly on the baseplate. By changing the distance between the two lenses note how the image on the wall forms. Have the students record their observations. The final configuration should have the lenses displaced by the sum-total of their focal lengths. The output light in this configuration will be collimated and the beam size should be magnified. This arrangement of lenses is the telescope.

Step 4: Have one member take an imprint of their thumb, place it on the acrylic and place it in the beam path. There should be a shadow of the thumb print already visible on the wall. Encourage laser safety; reminding students to not point laser pointers at anyone's eyes.

Step 5: Place the third and last lens in the optical path. Change the distance accordingly until a clear and large image is seen on the wall. This will happen when the lens is more that two focal lengths away from the wall. It will not depend on how far the third lens is from the acrylic pane. Encourage the students to measure and draw how large the beam is at every point in the path.

Imaging Ultrafine Features Worksheet

On the diagram below, draw what you think is happening to the laser light as it passes through each lens.



Connection to the Quantum Foundry

At the Quantum Foundry, scientists are working to develop materials that can be used in quantum computers. Thurst 2 is focused on the production of one-dimensional and two-dimensional interfaces that can be used in quantum information systems (QIS). These materials are built at the nano level meaning that scientists cannot easily see the materials they are working on without the assistance of high-tech devices such as electron microscopes. Rather than requiring to visually observe the materials they are building, scientists at the Quantum Foundry use methods similar to the ones explored in this Quantum Qit to make observations and gain knowledge about the shape, behavior, and position of the atoms.

Resonance frequencies (Program Cart 1) are used to determine the structure of atom-like systems such as NV centers or quantum dots. The only difference is instead of using sound waves, scientists at the Quantum Foundry use light waves and measure how the light waves change to determine the structure of their materials.

Magnetism is used in the exact same way at the Quantum Foundry as students explored in Program Cart 2; however, instead of large compasses to detect the changes in the magnetic field, scientists use single atoms to detect the smallest changes and map out the position of individual atoms within their materials.

Finally, to observe the shape and structure of the atomic materials they are building, quantum scientists use absorption imaging. Absorption imaging is where a laser beam is shone at a cold atom cloud and the shadow cast by the cloud (similar to Program Cart 3) is recorded by a CCD camera. The shadow cast tells scientists the optical density, or how much light can pass through, which is useful when figuring out how effective optical fiber is for transmitting information.