

PROPERTIES OF WAVES

Introduction: Properties of waves are fundamental to our understanding of how energy and information move through different media. These concepts are key to many technologies used in our society. Telecommunications use fiber optics and radio wave to transmit data. Ultrasounds, Magnetic Resonance Imaging (MRI), and X-ray technologies are based on wave behaviors to assist medical professionals diagnose and treat patients. Instruments and audio equipment rely on frequency and amplitude for pitch and volume. Waves are used by seismologists to study earthquakes and understand the Earth's interior. Electromagnetic waves help scientists study distant stars and galaxies. Wave properties also help scientists test, understand and develop technologies in the world of quantum mechanics.

Prior Knowledge:

Students should understand that waves can transmit energy.

NGSS:

HS-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.

HS-PS4-3 Evaluate the claims, evidence, and reasoning behind the idea that electromagnetic radiation can be described either by a wave model or a particle model, and that for some situations one model is more useful than the other.

HS-PS4-4 Evaluate the validity and reliability of claims in published materials of the effects that different frequencies of electromagnetic radiation have when absorbed by matter.

HS-PS4-5

Communicate technical information about how some technological devices use the principles of wave behavior and wave interactions with matter to transmit and capture information and energy.

ENGAGE

Waves in nature: Tsunami

There are many videos online including these below:

Tsunami: Race Against Time | Nat Geo

<https://youtu.be/fH2MtMByP10?si=JsK8cqNp2l7Nm8vI> See 10:17 and 19:18



The 2004 Indian Ocean Tsunami As It Happened (beginning has waves)

https://youtu.be/rZ_ae1N6t5Y?si=YIZW6SqjLkf3eUVh



General Background Knowledge/Relevance

Exploring examples of wave mechanics helps students build a conceptual and practical understanding of how waves behave. It assists with students understanding how these behaviors are applied to real-world technologies. Wave concepts like interference, diffraction, refraction, and standing waves can be demonstrated to allow students to visualize these concepts. This visualization will help students better understand the quantum connection and its relationship to technologies that shape our world.

PROPERTIES OF WAVES

Station 1 Snaky

Objective: Students will be able to identify key parts of a wave and visualize wave interactions and properties.

Materials/Supplies:

Snaky and/or Slinky™
Rope (approximately 2 meters).

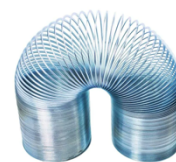
Part A: Slinky™ Snaky: Interactions at boundaries of different Media

The Snaky is a long helical ~1 inch diameter spring that can be used to demonstrate waves and other phenomena. A Slinky™ is a toy, a helical spring of a larger diameter that stretches more than the Snaky. Although both can be used in this explore, the snaky is less likely to get tangled and is therefore usually preferred.

A mechanical wave is a disturbance that moves through a physical medium without a net movement of matter. There are two ways matter can move to produce a wave: 1) the particles move parallel to the direction of the energy disturbance in longitudinal waves, or 2) the particles move perpendicular to the direction of the energy disturbance in transverse waves.

Waves react when entering a new medium. This will be explored using a Snaky and a Slinky™ connected or a Snaky and rope. A transverse pulse is a single disturbance produced by moving the Slinky™ or Snaky quickly to one side by “flicking” one’s wrist. A longitudinal pulse is created by holding a Slinky on the floor and quickly pushing it forward (parallel to movement) and then pulling it back.

Safety Information: The Snaky and Slinky™ should be handled carefully. All activities should be performed on the floor or a long lab table. If one or both ends are released while stretched, the springs can snap back quickly, possibly causing injury and damaging the equipment. Never let go of the springs unless they are slack as there is the possibility of serious damage to the eyes.



Slinky

Attach a spring (Snaky) and a Slinky™ together using wire or twist ties, zip ties, or strong string wrapped around the connection.



Snaky

Slinky



Snaky

Put the Snaky and Slinky on the floor and stretch it out for a reasonable distance as per your instructor.

NOTE: The distance is typically about 4 meters, just enough so the Snaky is slightly stretched. The Slinky will obviously stretch easier but be sure students do not stretch it too far nor just let it go. The latter will result in a mess of coiled springs that will not be salvageable. Typically assign someone to hold on to both and be very specific in telling them the consequences if they do not release them gently at the end.

Determine which medium is “more dense”.

Predict what will happen as a pulse travels the length of the connected pair.

Test the prediction and sketch what is observed: 1) before the pulse reaches the boundary and

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2) after the pulse reaches the boundary.

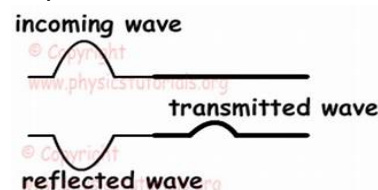
What happens to the phases of the reflected and transmitted pulses at that point?

Repeat, paying particular attention to the phase of the pulse as it reaches the boundary between the Snaky and the Slinky™ (specifically whether the pulse is on the right or the left of side of the Snaky or the Slinky™). What happens to the phases of the reflected and transmitted pulses at that point? Does the Slinky move the same direction (L or R) as the Snaky was moving? Does the part of the wave that is reflected back onto the Snaky move in the same way the incoming wave was moving? Make sure this is accurately portrayed in your drawing. Compare with peer's drawings.

Ans: Part of the wave is transmitted, and part is reflected. The transmitted and reflected pulses are smaller. The reflected portion will not have a phase change.

Is the result the same when the pulse is sent from the Slinky™ to the Snaky? Make a new drawing if it is not. Include information about the original and transmitted pulses.

Ans: A portion of the wave will still be transmitted, and a portion will be reflected. The reflected portion will have a phase change. When a pulse goes from the Slinky™ to the Snaky the reflected pulse will be out of phase because the pulse is going from a less dense medium to a denser medium.



Summarize your observations about the phases of the original and transmitted pulses in 1-2 sentences.

Part B: Snaky: Reflections from fixed or free end boundaries

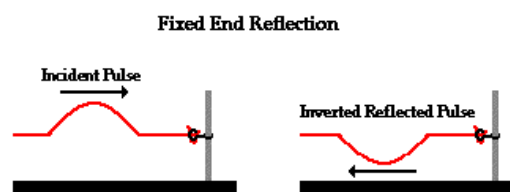
This section will explain why the reflected pulse differed depending on where the pulse originated.

Using only a Snaky attach approximately 2 m of string or rope to one end.

Send a pulse from one end while holding the opposite end of the spring tightly to simulate a rigid barrier.

1. How do the phases of the original and reflected pulses compare when a wave is reflected from a rigid (or fixed) barrier?

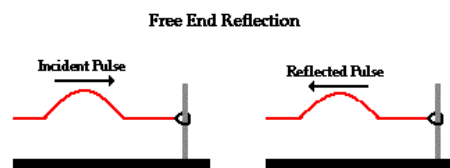
Ans: The reflected pulse will be out of phase from the original pulse.



Send a pulse from one end of the rope while holding the opposite end of the spring loosely by the string to simulate a non-rigid barrier.

1. How do the phases of the original and reflected pulses compare when a wave is reflected from a non-rigid barrier? ¹

Ans: The reflected pulse will be in phase with the original pulse.



2. Which type of barrier was represented by the pulse going from the Snaky to the Slinky™?
Ans: more to less dense

Part C: Snaky: Superposition and Interference

¹ Image source: physicsclassroom.com

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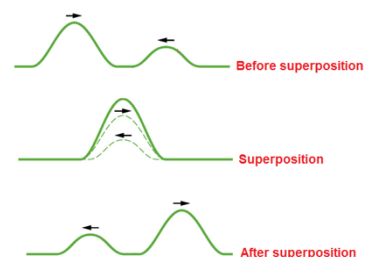
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The principle of superposition states that when two or more disturbances (pulses) occupy the same space at the same time the resulting disturbance or pulse is the algebraic sum of the amplitudes (heights) of each pulse. Following the interaction the pulses pass through each other, each continuing in its original direction of travel, and the original amplitudes remain unchanged. Constructive interference occurs when two or more pulses meet each other to create a larger pulse. Such as crests meeting or troughs meeting. Destructive interference takes place when two or more pulses meet and result in a smaller amplitude disturbance. For example, a crest meeting a trough may result in an amplitude of zero or anything less than the largest amplitude.

Using pulses that are both pulled to the side (transverse pulse). Experiment with pulses of the same and different sizes and with pulses in phase (same side) and not in phase (opposite side).

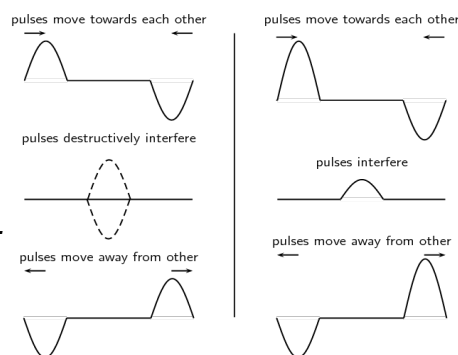
- What happens when the pulses meet? Do the pulses appear to pass through each other or do the pulses “bounce back” from the collision with another pulse?

Ans: The pulses pass through one another



- How does the maximum displacement (amplitude or height) where the pulses meet compare with the displacement of each pulse prior to the interaction?

Ans: If the pulses are on the same side the displacement is larger than either pulse alone. (Constructive interference) If the pulses are on opposite sides the displacement is smaller than either pulse alone. (Destructive Interference)

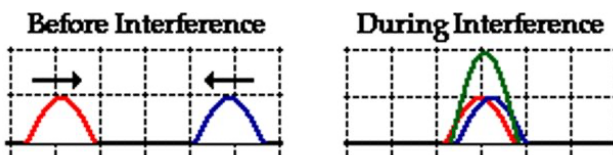


- Sketch your observations including sketches of before pulses meet, when the pulses meet and after the pulses meet.

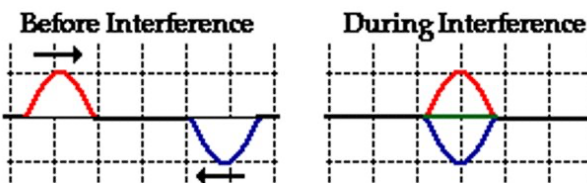
Interference is the phenomenon that occurs when two waves meet while traveling through the same medium. The interference of waves causes the medium to take on a shape that results from the net effect of the two individual waves upon the particles of the medium. When two upward displaced pulses having the same shape meet up with one another while traveling in opposite directions along a medium, the medium will take on the shape of an upward displaced pulse with twice the amplitude of the two interfering pulses. This type of interference is known as **constructive interference**. If an upward displaced pulse and a downward displaced pulse having the same shape meet up with one another while traveling in opposite directions along a medium, the two pulses will cancel each other's effect upon the displacement of the medium and the medium will assume the equilibrium position. This type of interference is known as **destructive interference**.

For the following diagrams Red=Wave 1, Blue=Wave 2, Green=Result of the combination

Constructive Interference:



Destructive Interference:



Wave Terminology

Crest – The highest point or peak of a transverse wave above the rest position (equilibrium).

Trough – The lowest point of a transverse wave below the rest position (equilibrium)

Wavelength – The distance between two consecutive points in phase on a wave. Common measurement is between crest to crest or trough to trough.

Wave Height – The vertical distance between the crest of a wave and the trough of a wave.

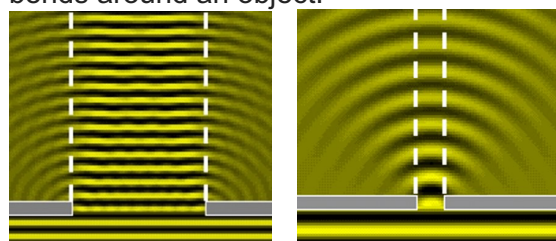
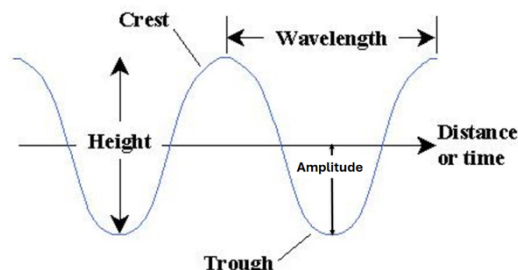
Amplitude – The maximum displacement of a point on a wave from its rest position. One half of the wave height.

Frequency – How many wavelengths pass a fixed point each second.

Reflection – Occurs when a wave strikes an object and bounces off of it.

Refraction – The bending of a wave caused by a change in its speed as it moves from one medium to another.

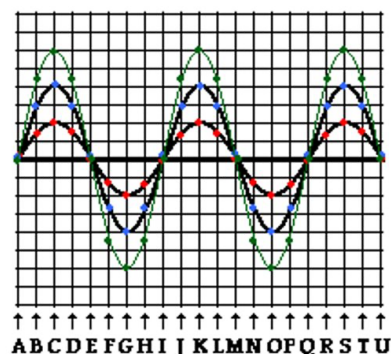
Diffraction – The property of waves where an object causes a wave to change direction as it bends around an object.



Wave Interference – The combined effect of individual waves meeting at the same place and at the same time.

Constructive Interference – When two or more waves overlap and their displacements add together, creating a wave with greater amplitude.

Destructive Interference – When two or more waves overlap and their displacements cancel each other out, resulting in a wave with reduced or zero amplitude.



Principle of Superposition – When two or more waves cross at a point, the displacement at that point is equal to the sum of the displacements of the individual waves. Video link for standing wave:

<https://youtu.be/zBMAddLjCKA?si=d4Hb7q2LeyvrDEHq>

EXPLORE
Station 2
Modeling Superposition

NOTE: This activity is a modification from *The Perimeter Institute's Resource: Investigating the Nature of the Electron* — <https://perimeterinstitute.ca/outreach>. For more activities on gravitational waves go to *Perimeter Institute Resources: Wave Model Applications or Gravitational Waves*

1. Use the transparencies provided and place one on top of the other so they “match” and look like one wave.

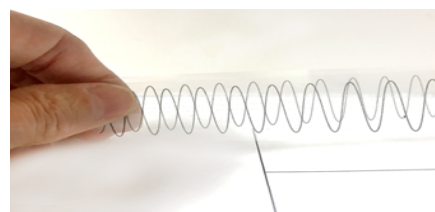
Observe at several intervals and sketch how the resulting wave would appear.

2. Slowly slide ONE of the transparencies to the right.

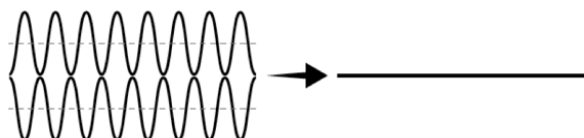
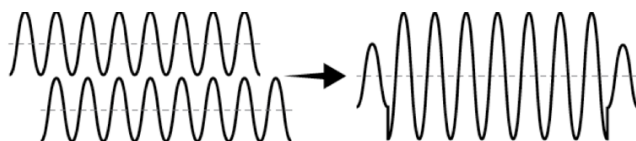
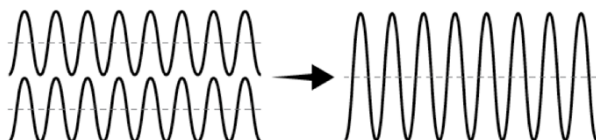
Observe at several intervals and sketch what the resulting wave would appear. Describe how this interference relates to superposition and how the amplitude would be affected.



ANS: The top part (arch) of the wave is called a crest, and the opposite (going down) is called a trough. When two waves overlap it is called superposition. When two arches match up (same direction) it is called constructive interference, and the amplitude is the sum of the two individual amplitudes. When they do not match up, it is called destructive interference, resulting in less amplitude than the larger original amplitude. Below are some examples students could model with the wave transparencies. The resultant wave is shown on the right side of the arrow.



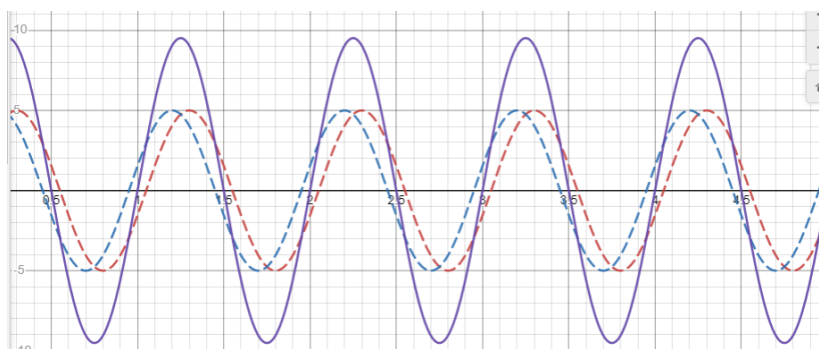
Identify the type of superposition (constructive, destructive).



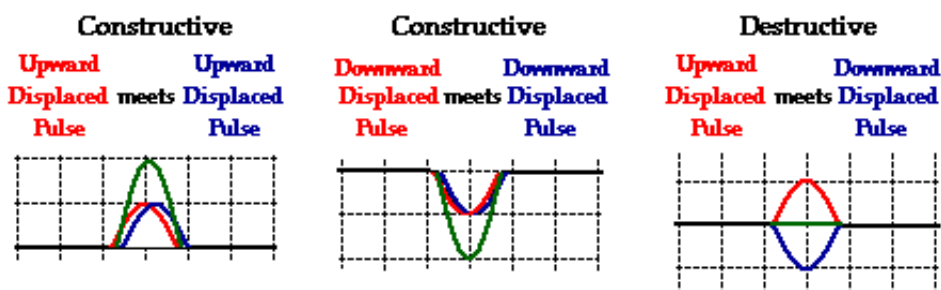
EXPLORE Station 3 Desmos Simulation

Open the Desmos Standing Waves Simulation <https://www.desmos.com/calculator/nk2ggsfk9k> and screen or phone capture different interference patterns. The Red Wave is #1, the Blue Wave is #2 and the purple wave is the superposition of the two waves. Vary the frequency (i.e. change the wavelength), run the simulation, pause the simulation and sketch the resulting waveform due to the superposition of the red and blue waves. Repeat at least 3 times.

Teacher notes: When the red and blue wave crests overlap the waves are in phase and the greatest interference takes place. In the image below the red and blue waves are out of phase.



1. Discuss with your group where there was constructive and destructive interference in the activity.
2. The diagrams below show two waves (i.e. similar to in a Snaky) where one is blue and the other is red. The waves are interfering in such a way as to produce a resultant shape in a medium; the resultant is shown in green. In two cases (on the left and in the middle), constructive interference occurs and in the third case (on the far right, destructive interference occurs.



EXPLORE Diffraction

For more detailed background, go to IQC Educator's Guide: [Measuring the Width of Your Hair](#)

Objectives:

Students will explore the behavior of wave diffraction.

Students will understand interference is a wave property that occurs when two waves meet and interference applies to multiple systems, including those on the quantum-mechanical scale.

Understanding interference is key to quantum technologies including quantum computing and quantum sensing.

Materials/Supplies:

Laser pointer (red laser)

A strand of hair

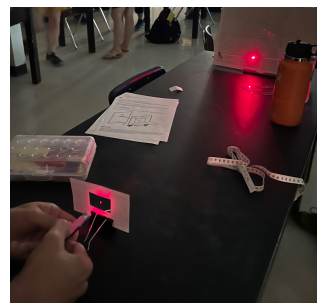
Measuring tape/ruler/meter stick

Whiteboard or wall with paper

Tape, Index card, medium binder clip (as a stand), scissors

Calculator

Laser Safety sheet to be at each station/group



Instructions:

Divide students into smaller groups so half the room (half the groups) will have red lasers and half will have green.

Student instructions are provided in the Appendix.

1. Mount the hair so it stands vertically.
2. Create a long, clear path from the mount to the wall.
3. Measure the distance “d” from the hair to the wall.
4. Shine the laser onto the wall or white board through the hair. Be sure to keep the laser steady.²
5. Observe the pattern made by the laser hitting the hair. Trace the pattern in the space provided on the worksheet.
6. Measure the separations “s” between the dark spots.
7. Calculate the width “w” of your hair using the following formula:



$$w = \frac{2d\lambda}{s}$$

w = hair width

d = distance from the hair to the wall

s = separation of dark spots

λ = wavelength of the laser

Have students compare the separations between the dark spots for different colored lasers. They may do a gallery walk to observe experiments of different groups to compare different type, colors of hair, and textures. If there is time, they can put multiple hairs on one index card to compare patterns.

² This can be done by setting the laser on a book or another support which could also be an engineering design project.

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The relationship between the width of the hair and the size of the pattern is not what one might expect. A smaller hair results in a larger interference pattern, the opposite of what we would expect from other behaviors of light like shadows. A full derivation of the formula is possible with some trigonometry (see Appendix), but there are easier, hands-on ways to convince students that this is the case.

Gauge (AWG)	Width (mm)
24	0.511
28	0.321
30	0.255
34	0.160

Introducing the activity by showing students objects with a known width and demonstrating that thinner objects produce wider diffraction patterns. Jewelry wire is particularly useful for this, as it comes in a variety of sizes that are easy to distinguish by eye and produce clear interference patterns, with 28-34 gauge being particularly effective and easily accessible at craft stores or online retailers. Most human hairs are between one hundred and one thousandth of a centimeter wide. Students may be interested in comparing different types and colors of hair, including artificial hair.

Alternative options include using a laser printer to print either lines or slit on overhead transparencies. Most laser printers have a resolution of 600 dots-per-inch (dpi), translating to 0.04 mm, making it possible to print objects comparable to the width of a hair. The patterns, while quite visible, will not be as clean as the hair or wire since the printer leaves gaps between the dots that produce other interference patterns. A third option would be to use a 3D printer, where the height resolution (layer height) can be as small as 0.1 mm.³

Lasers need to be low wattage for safety.

Red laser wavelength = 650 nanometers = 6.5×10^{-5} cm

Green laser wavelength = 532 nanometers = 5.32×10^{-5} m

A darker room is ideal for seeing the interference pattern of the laser on the wall. Students will be able to see the constructive and destructive interference patterns (bright and dark spots). To see the interference pattern clearly and gather accurate measurements, the mount for the hair should be at least 2 meters away from the wall.

Make sure to review laser safety with students before performing this activity.

Groups of 2-3 students are recommended for this activity. Turning the lasers may give a clearer diffraction pattern, especially if using inexpensive lasers.

Students should share findings and observations from the Explore activity and the teacher will introduce concepts and vocabulary on parts of a wave and terminology as appropriate. Teachers should emphasize that different wavelengths produce different gaps in the diffraction patterns (red and green lasers) and therefore diffraction can be used to separate colors. Students can also use diffraction glasses to see that diffraction separates the colors of white light by viewing ceiling lights. Refraction will also spread out the spectrum, which is explored in the next section.

³ For more detailed background, go to IQC Educator's Guide: [Measuring the Width of Your Hair](#)

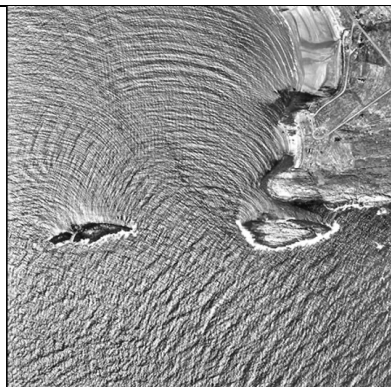
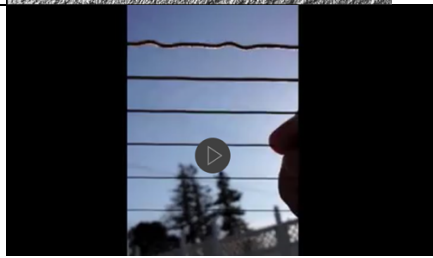
EXPLAIN and REVIEW Overview

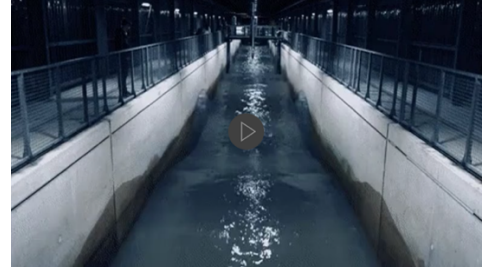
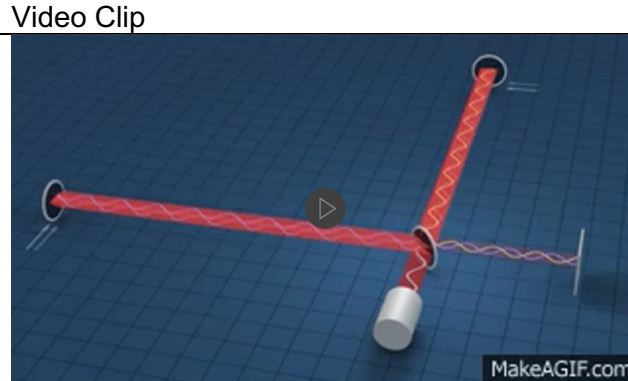
View the Veritasium video: The Original Double Slit Experiment (start around 4:00)

<https://youtu.be/luv6hY6zsd0?si=1TTXR4sOLxFQC-2W>

Photos and videos can be utilized to help students identify different properties and components of waves such as the one shown. One suggestion would be to assign a wave property to each group and have students find their own examples or even find an example with multiple properties. The following images and video clips may be used for group evaluation or individual evaluation. Have students identify the terminology/vocabulary related to wave properties.



Evaluate Image/Video	Possible Responses
	Diffraction Wave Interference Superposition Wavelength Frequency Crest Trough
 Video Clip	Wave Heights Amplitude Standing Waves Crest Trough
 Image	Wave Interference Constructive and Destructive Interference Superposition Amplitude Wave Height Wavelengths Crest Trough

	Video Clip	Standing Waves Amplitude Wave Height Crest Trough
	Video Clip	Reflection Wave Interference Constructive and Destructive Interference Superposition Crest Trough Wavelength Frequency
	Video Clip	Wave Interference Constructive and Destructive Interference Superposition Crest Trough

PROPERTIES OF LIGHT In MEDIA

Light interacts with materials in non-intuitive, but predictable ways. When light hits a material, some light may bounce off, and this is called reflection. As light passes through materials, its speed may change, causing objects to appear bent, like a pencil in a glass full of water. This is called refraction and the index of refraction (or refractive index) describes how much the path of light is bent when passes from one medium to another. Some materials will have different speeds for difference wavelengths, causing a beam of light passing through the material to be spread out according to wavelength. This is why one can use a prism to produce the rainbow spectrum. All these effects are predictable, and one can use these effects to make useful devices. For example, one can use the refractive properties of glass to bend light to focus it or spread it out for a specific purpose. We call such a device a lens, which we use to make glasses, telescopes, and microscopes.

NGSS:

HS-PS4-3 Evaluate the claims, evidence, and reasoning behind the idea that electromagnetic radiation can be described either by a wave model or a particle model, and that for some situations one model is more useful than the other.

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HS-PS4-4 Evaluate the validity and reliability of claims in published materials of the effects that different frequencies of electromagnetic radiation have when absorbed by matter.

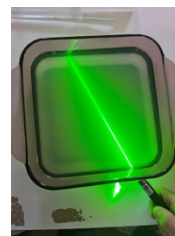
HS-PS4-5

Communicate technical information about how some technological devices use the principles of wave behavior and wave interactions with matter to transmit and capture information and energy.

EXPLORE Light Through Different Media

Materials/Supplies:

Lasers (alternate different color lasers if available)
Gelatin or Jello cubes (see below for instructions) OR acrylic/glass blocks
Twisted acrylic tube or optics tubing
Protractor or polar graph paper
Sheets for laser safety at each station



If materials are available, use refraction cups with different clear liquids (i.e. water, oil, soap, etc.) to help students see how materials bend light differently.

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Objective: Students will observe reflection and refraction of light in different media.

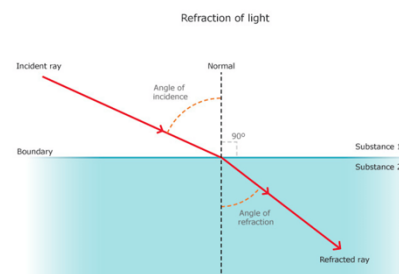
Gelatin or Jello Cubes Procedure

Preparing the Gelatin Block:

- Mix gelatin powder with warm water according to the instructions. Adding more gelatin (3x as much as in box recipe) is often preferred to reduce chance of liquification during class.
- Pour into a mold (hint: spraying with Pam helps with removal) and let it set in the refrigerator until firm (3-4 hours or overnight).
- Once set, remove it from the mold. If needed, trim into a rectangular block(s) or various shapes.
- Place on a paper plate or flat surface for the activity.

Refraction:

- Place the glass or gelatin block (i.e. clear lens) on a paper plate or flat surface. It is often useful to place polar graph paper underneath and sketch around the shape of the lens.
- Lay the laser on the table and shine at an angle into the lens from the outside. Mark the point of entry into the lens. Align a ruler with the beam as it enters the lens and draw this as the incident ray.

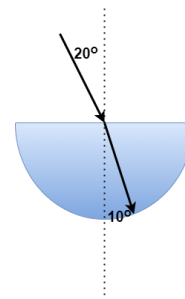


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QUEST

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- Observe how the beam bends (refracts) as it hits the barrier and again as it leaves the barrier. Align the ruler with the exiting refracted ray (opposite side of the lens when the beam exits) and draw again. Remove the lens, mark the normal line at the point of incidence and mark the “different” normal line at the point where the beam exits the lens.
Note: A normal line is perpendicular to the barrier surface.
- Change the angle of incidence and notice how the angle of refraction changes.
- (Optional) Use a protractor, polar graph paper, or draw lines on paper to measure the incident and refracted angles.
- If using a refraction cup, shine the laser on the flat side of the cup and notice it only bends at the initial surface, not as it exits.



Internal Reflection:

- Shine the laser inside the lens, aiming toward the inner surface at a shallow (i.e. close to the entry point) angle.
- Gradually increase the angle until the beam is reflected completely inside the lens without escaping. This is total internal reflection.
- Observe that at some angles, very little light escapes. However, past a certain angle it reflects fully. Compare results of the different angles.

Repeat the activity with different colored lasers. Record observations and then compare to another group.

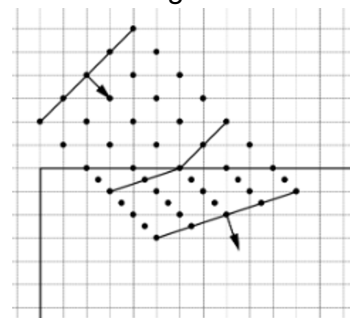
EXPLAIN

The speed of light is always constant in a vacuum. However, in materials (acrylic, glass, gelatin) light appears to travel slower. This is NOT because photons slow down, but because of how they interact with the material. Light is an electromagnetic wave. When it enters a material, it interacts with the electrons in the atoms. Photons travel between the atoms at the speed of light, (c), but as they hit atoms, they get absorbed and re-emitted, or they induce oscillations in the electrons which then radiate new waves. This repeated interaction causes a delay in the forward progress of the wave. Therefore, the overall effective speed of light through the medium is reduced. This is called the group velocity or phase velocity.

$$n = c/v$$

n=refractive index of a material; c= speed of light in a vacuum; v=speed of light in medium

To help students to conceptually understand why the light will bend while slowing down and not for a medium entering perpendicular to the surface (i.e. along the normal), it may help to use a graph to plot points similar to what is shown. Start with a plane wave front and progress through time as it passes through a medium of greater density. As the right side of the wave touches the boundary it will begin to interact with the particles in the medium and the result is a slowing down for the portion of the front that is now in the medium. The wave front that is still in air (or outside the medium) will continue at the same speed until it hits the medium.



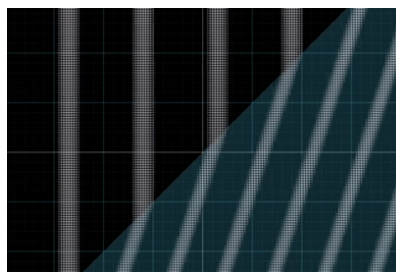
For more detail, consider watching the first part of Veritasium “What they don’t teach you about rainbows at school” which can be broken down into subcomponents and utilized to explain the refraction of light in relation to phase changes.

Part 1 (1- 6 min) is on the bending of light.

<https://youtu.be/24GfgNtnjXc?si=ZaZlqFbzBHRlhHh9>



Part 2: 9-11 min. shows oscillations and frequencies (analogy to pushing swing). Higher frequency will cause the charges to wiggle with greater amplitude resulting in higher amplitude EM radiation which creates a bigger phase kick, which shortens the wavelength proportionally more resulting in higher frequency light traveling slower and bending more than lower frequency light.

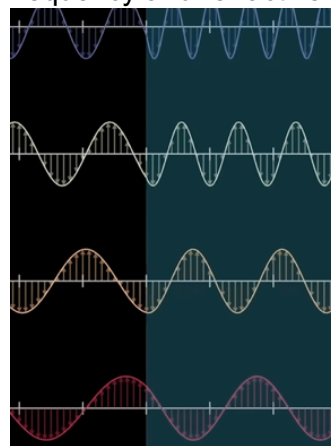
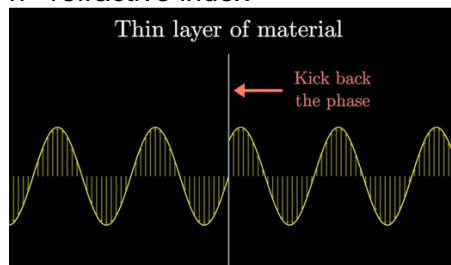


When light travels between different media, its speed (v) and wavelength (λ) change (e.g. decrease), but its frequency (f) remains constant according to the equation $v = f \lambda$. The wavelength within the medium is determined by the frequency and refractive index of the medium.

$$v = \frac{c}{n}$$

c = speed of light in a vacuum

n = refractive index

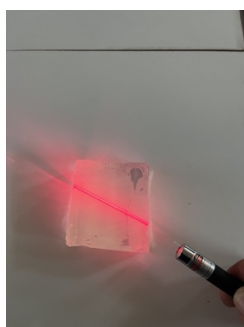
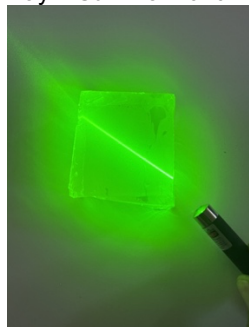


Summary: Light causes the charges to wiggle, so they create their own EM wave which gives the light a phase kick shortening its wavelength which slows it down. Refraction separates colors because different colors bend differently as they pass through materials. This spreads the white light out into components, called the spectrum. These are the colors seen in a rainbow (next section).

Khan Academy video on Refraction and Reflection

<https://youtu.be/LKl1UmFbfaA?si=sHFQn5pAf3OVn-DU>





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Discussion questions:

- What happens to light as it passes from air to the gelatin (or acrylic block)? *It slows down and bends toward the normal line.*
- Why does total internal reflection happen only when light travels from gelatin to air (or the acrylic block to air)? *Total internal reflection only happens when light travels from a more optically dense medium to a less dense one. In the case of these examples the gelatin and acrylic blocks have a high refractive index compared to air. When light goes from a dense medium to a less dense medium it bends away from the normal line. As one increases the angle of incidence, the refracted ray bends more and more until it reaches a certain angle called the critical angle. At that point the refracted ray travels along the boundary. If the angle is increased past the critical angle the light cannot escape at all. It is reflected back into the medium. This is total internal reflection.*
- Does the use of different colored lasers affect the results of refraction? *Yes. Different colored lasers have different wavelengths and do affect the angle of refraction of the beam. This is due to "dispersion." Dispersion is a phenomenon where different wavelengths of light travel at different speeds when passing through a medium. A classic example is the separation of white light into different colors when it passes through a prism. Different wavelengths of light have different frequencies, so the electrons in the material vibrate differently in response to each one. When light enters the medium its electric field pushes on the electrons of the medium. If the light's frequency is close to the natural frequency of the electrons, they interact more strongly. Light slows down more, meaning a higher refractive index. For visible light, shorter wavelengths (blue, violet) tend to be closer to these resonances than the longer wavelengths (red). Therefore, blue light bends more. Red light bends less.*

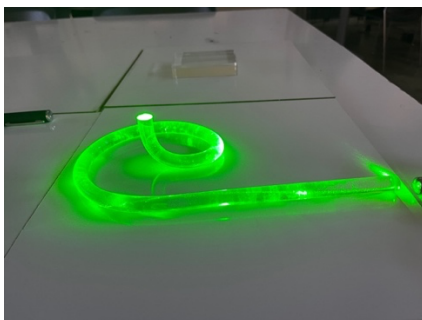
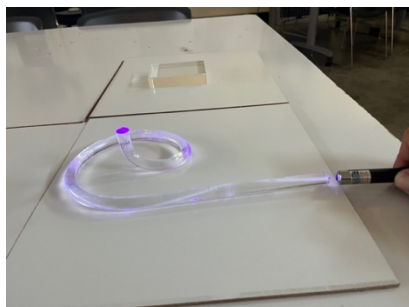
Twisted Acrylic Tube or Optical Cable

- Shine a laser into the end of the twisted acrylic tube or optic cable.
- Adjust the angles of the laser and observe what happens in the medium.

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- Adjust the angle so that the light is reflecting inside the filament or tube (i.e. internal reflection).
- Compare observations using different colored lasers.



Total Internal Reflection (TIR) is the key that makes fiber optic communication work. TIR keeps the light signal trapped inside the fiber allowing signals to travel long distances with very little loss. Fiber optic cable consists of a core of thin glass or plastic with a high refractive index. It is surrounded with a cladding that has a slightly lower refractive index. If the angle of the light beam is greater than the critical angle the light inside the hits the core-cladding boundary and undergoes Total Internal Reflection. Total Internal Reflection keeps the light bouncing with in the core even as the cable bends or stretches.

Quantum connection: Photons as information carriers.

In quantum optics, information can be encoded in single photons. This is how quantum communication and quantum cryptography (Quantum Key Distribution –QKD) work. Fiber optics allow these photons to be transmitted without disturbing their quantum states, which is key to their secure communication. Entangled photon pairs can be created and sent through fiber optic cables. These are key to quantum networks, where quantum information (qubits) is shared securely between distant locations.

Quantum connection: Fiber Optic Sensors

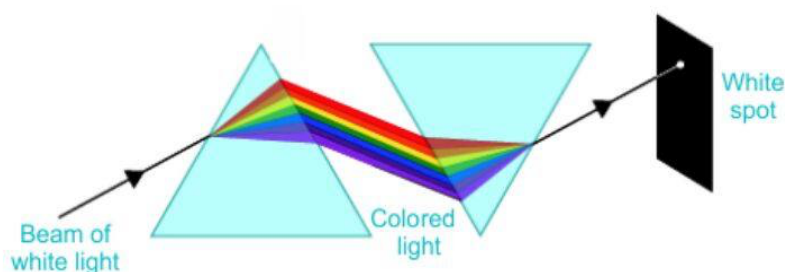
When light undergoes total internal reflection at the boundary between the fiber's core and the cladding, not all of it stays perfectly inside the core. A small amount of the electromagnetic field gets into the cladding. This called an evanescent wave or evanescent field. This evanescent field behaves a lot like a quantum tunneling wavefunction. In quantum mechanics a particle can "leak" into a region it classically should not be able to enter. Similarly light "leaks" just outside the fiber even though it is under total internal reflection. If the cladding is removed or thinned and the evanescent field is allowed to interact with the environment then any change in that environment will alter the evanescent wave. Environmental change examples can be the presence of chemicals or pollutants. These changes affect the light's intensity, phase, or polarization, which can be measured. Biosensors, chemical sensors, and environmental detectors using optical fibers use this principle.

ENGAGE

Components of Light (Newton Experiment)

Overview of the lesson:

Students should observe that white light is a spectrum of colors ranging from red to violet. If a second prism is placed in front of the individual colors of the spectrum, there should be a spread of only the selected color of light. The lack of different colors means individual colors of light cannot be further broken down.



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Student Instructions The Newton Experiment

Materials/Supplies:

- Single LED flashlight or incandescent light (Maglite, penlight, etc.)
- Cover with a slit (cardboard, cardstock, etc.)
- Two prisms
- Index card/screen
- Paper tube (for added beam effect)



Objectives:

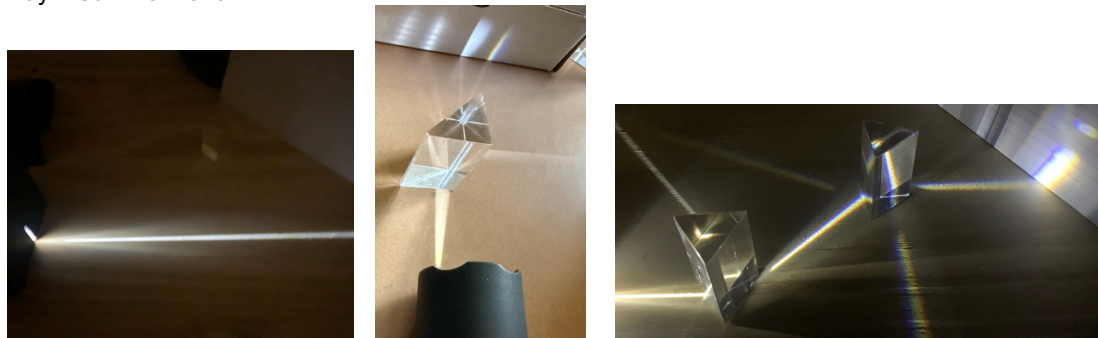
Students will be able to observe the spectrum of white light as it passes through a prism and separates the colors red, orange, yellow, green, blue, and violet (ROYGBIV).

Students will be able to observe how light colors can be recombined back to white light by going back through a second spectrum.

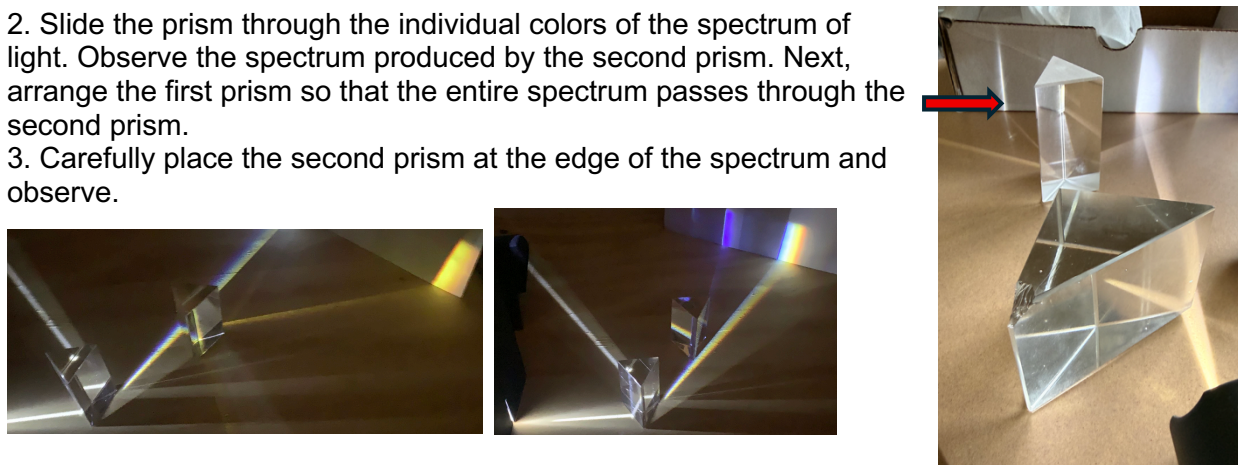
Procedure:

1. Place the light source behind a narrow slit. For a long, narrow beam, a tube, such as a paper towel tube, can be used. A narrow slit and intense light source will have the best result. Next, place the first prism in front of the beam of light. Arrange the prism to form a spectrum.





2. Slide the prism through the individual colors of the spectrum of light. Observe the spectrum produced by the second prism. Next, arrange the first prism so that the entire spectrum passes through the second prism.
3. Carefully place the second prism at the edge of the spectrum and observe.



EXPLORE Light and Energy (Herschel)

Introduction: A historical thread is used to link activities in this learning cycle. Starting with the premise that light is an electromagnetic wave, there is energy in light that cannot be seen, and the only way to understand why hot objects glow is to assume that light comes in fixed quanta where the energy is proportional to the frequency of the light. In describing blackbody, it does not mean that the “body is black” but rather all the radiation comes from the temperature and not from reflection.

Prior Knowledge:

Light is electromagnetic radiation

Light carries energy

Electromagnetic spectrum includes several types of radiation including visible light.

Wavelength and frequency of waves

Background:

Scientists had to first understand that light is energy before understanding blackbody radiation (i.e. energy being radiated by an object).

In 1800, Sir William Herschel demonstrated the existence of infrared radiation by measuring temperatures in different parts of the visible spectrum and beyond. Initially he was looking for a filtering material to reduce the brightness of the Sun’s image in the telescope during solar observation. This discovery proved that light carries energy and there was light energy beyond the visible spectrum.

Herschel used a prism to separate sunlight into its colors (spectrum), then placed thermometers with blackened bulbs in different parts of the spectrum, including beyond the red end, to measure the temperature. The experiment revealed that the highest temperatures were found not within the visible spectrum, but rather in the region beyond the red, indicating the presence of invisible "calorific rays" now known as infrared. The highest temperatures within the visible spectrum were in the red portion of the spectrum.

The experiment established that infrared radiation is a form of electromagnetic radiation, invisible to the human eye but still capable of transmitting energy. His experiment was important in the quest to understand the nature of light and the electromagnetic spectrum and paved the way for various applications.

The question of why absorbing light from the red end of the spectrum would result in warmer materials compared to absorbing blue light does not need to be explained for this activity. However, teachers should be aware that red light is more effective at producing molecular vibrations than blue light. Temperature is a measure of the random vibrations of the particles in a substance, so red light warms materials more effectively than blue light. Blue light is more effective than red light in producing atomic electronic transitions, but absorption of energy that produces an electronic transition does not result in greater random motion of the particles (atoms and molecules) and therefore does not contribute to the temperature. Herschel did not know any of this nor what light was or how random molecular motion was related to temperature. He documented what he saw and that invisible light carried heat, even though no one understood the concept of light or heat or atoms or molecules.

Instructions

Materials/Supplies:

Prisms, paper, colored markers, digital temperature probes, Graphical Analysis app or thermal probe with means of collecting data.

Objective:

Students will observe (using temperature probes) and compare various portions of the spectrum (visible, nonvisible) and determine that "nonvisible" portions of the electromagnetic spectrum have light energy and therefore light is energy.

Teacher Notes: It is visually helpful to have the students color the spectrum as many have never noticed the colors are in a specific order. It may be useful to have them predict the order of the colors before they go outside.

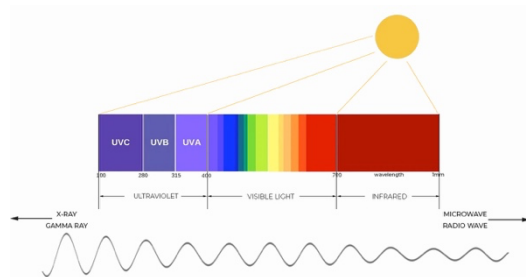
A normal thermometer does not normally pick up the temperature well enough for students to see much difference. Electronic thin, surface temperature probes work best. Have students predict whether the temperature will be higher in the shade or in the area just outside the red portion of the rainbow (which they will also consider to be shade). The temperature will be highest in the infrared (non-visible) portion of the EM spectrum. Photo credit⁴

⁴ <https://images.app.goo.gl/ve16pzcqHZfgBEa86>

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A prism is held so that sunlight casts a rainbow on a piece of paper. A temperature probe should be placed: 1) in the rainbow towards the red portion of the spectrum, 2) just outside of the rainbow on the red end of the spectrum, and 3) in the shade (i.e. they move the paper to be in the shade of a tree). The temperature will be highest in the infrared (nonvisible) portion of the EM spectrum. UV light (outside of the visible region on the blue side of the spectrum) has shorter wavelengths and higher energy, while infrared light has longer wavelengths and lower energy.

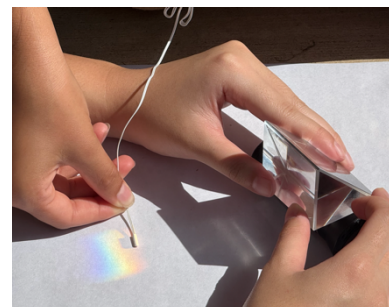


The fact that to the right of the red, beyond of the rainbow, the thermometer still registers a higher temperature can be a mystery to students. When students take the temperature in the shade, it will likely be less than the infrared (IR) reading but will be more than the visible spectrum. The exact amount of the temperature difference between the ambient temperature and the temperature in the red or the infrared will depend on the dispersion of the light (size of the rainbow), but it will be on the order of several degrees Fahrenheit. It is a clear indication that the energy in the white light that was spread out by the prism extends beyond the visible range. With this information, one can now talk about the electromagnetic spectrum as a whole and what distinguishes the different colors are the different wavelengths of electromagnetic waves.⁵



Overview of Lesson:

Herschel experiment: Light (visible and infrared) is energy. Students use a prism in the sunlight to identify the visible parts of the spectrum, then take the temperature at a point near the red portion of the spectrum (visible spectrum) and outside the visible spectrum (infrared spectrum). The temperature in the infrared spectrum, although it cannot be seen, indicates the presence of energy and is higher than the visible spectrum. The Herschel experiment is important because it led to the discovery of infrared light and it was shown that there were forms of light we cannot see with our eyes.



Teacher Background

It is important to NOT allow students to compare thermometer readings in different colors in the rainbow. If measured, students will find the temperature in the blue is lower than the temperature in the red. This could lead students to conclude that red light is “hotter” or more energetic than blue light. This would be reinforced by the commonly used “rainbow color scale” in which red is “hot” or maximum and blue is “cold” or minimum. While other perceptual features of a representation can overcome the tendency to default to the rainbow color scale, in this case the common experience with the rainbow color scale along with the observation of a higher temperature in the red compared to the blue would lead students to a strong

⁵ The Quantum for All Students and Teachers Project: Sample Activities and the Historical Storyline Linking Them, The Physics Teacher Jan 2025 [TPT25](#)

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misconception that red light is more energetic than blue, exactly the opposite to reality. Once students acquired this idea through their own experimentation, supported by prior knowledge, it would be exceptionally difficult to undo this mistaken concept. This would impede learning about photons as quanta of light since blue photons are more energetic than red photons. If students do observe the varying temperature and bring up the issue, a teacher could say that the total amount of energy, or intensity of the light, varies with color/wavelength so one cannot not draw simple conclusions other than that not all light is visible. The blue Lego quanta are bigger and have more energy but there are fewer of them.

EXTEND

Anodization has many industrial applications. It is an electrochemical process that transforms a metal's surface into a durable, corrosion-resistant finish. An advantage is that it works by thickening the naturally occurring oxide layer of a metal resulting in full integration to the underlying substrate. This results in a permanent structural alteration of the surface so it never peels or flakes and therefore can last over 50 years while colored finishes generally last 10-20 years depending on the dyes being used.

Anodization thickness is usually measured in nanometers down to a few micrometers. The visual effect of anodization is like a thin film interference and can act as an optical filter creating iridescent colors purely through light manipulation rather than by using dyes.

Anodization and thin film optics:

Students are likely familiar with seeing "oil slicks" on the road or water. This is referred to as thin film interference and can be duplicated in many ways including placing a small drop of clear nail polish on water and then sliding a piece of paper underneath film to remove it (often called water marbling or rainbow paper). Nail polish and water do not mix but instead the polish will spread an ultra-thin layer. Collecting the layer is a little tricky, but students, young and old, enjoy seeing the patterns that can be created. Having students do this after going through the lessons color should reinforce their understanding and allow for discussions into other applications such as the process of anodization and using Scanning Electron Microscopes to see how particles are aligned.



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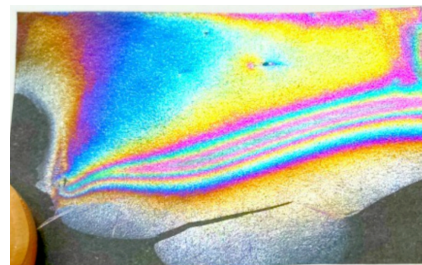
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Many students may have used a similar process to create unique patterns on their fingernails. Other resources or videos:

<https://carbondalepubliclibrary.org/odd-paints/>

Procedure for Making Rainbow Paper (thin-film interference):

1. Use a shallow bowl or container filled with about 1-2" of water. It is advisable to place the container on a towel or surface that will not be harmed when getting wet as there are usually extra drips of water as the card is removed.
2. Place a single drop of clear nail polish (colored polish will produce more marbling, clear give the rainbow effect) carefully on the surface of the water. Do not use a gel polish. If students want to experiment with more colors the drops should be added quickly.
3. Use a half sheet of construction paper (black usually works best but white can be used) and slide it into the water

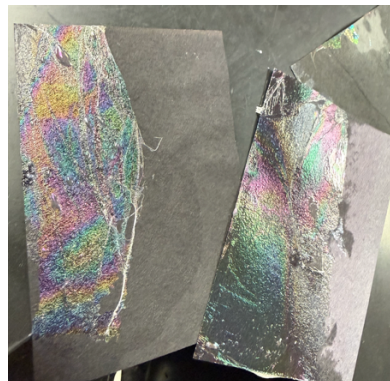
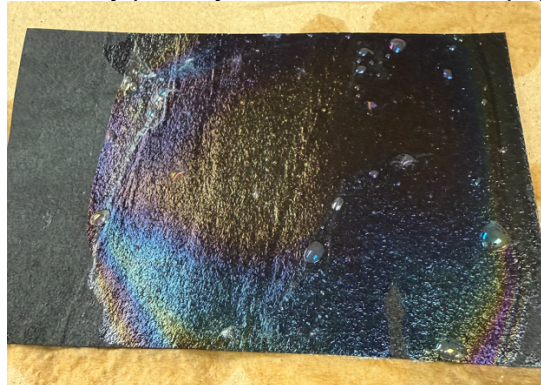


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at an angle being sure to fully submerge under the film. Slowly lift the paper straight up through the film catching the film on the surface of the paper.

4. Gently pat any excess water off the paper and lay flat on towel to dry.



Teacher Background Notes:

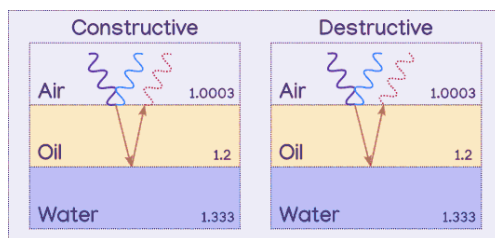
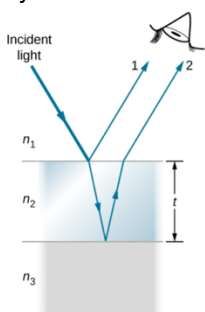
When the nail polish spreads across the water, it forms a microscopic film that is only a few hundred nanometers thick. When white light hits this layer, it reflects off both the top of the polish and the bottom of the polish. This is called thin-film interference.

Because the film is so thin, these light waves bounce into each other and interfere (constructively and destructively) and as the paper is rotated, students will notice the colors change. This is due to the light hitting the paper at different angles as it moves and the colors of the rainbow vary with the thickness of the nail polish on the paper. Different thicknesses in the film emphasize different wavelengths of light, breaking them into brilliant, iridescent rainbow colors. This is the exact same optical phenomenon you see in soap bubbles or an oily puddle in a parking lot. As you change the angle at which the light hits the film, the light comes in at a shallower angle, then the ray that enters the film will travel a longer path in the film, and be slowed down more than before and comes out the top a little later. If the film is thicker, the ray that travels inside the film has farther to go and again comes out of the top a little later.

One thing to notice is that the rainbow colors often appear in rings. The outermost edge of the film is usually colorless because the film there is thin and often a single molecule thick and thinner than a wavelength of visible light. Inside that edge the first ring of colors shows where the thickness of the film is first in the range for making colors. The inner rings are seen because the film is thicker and the waves of light are lining up where one ray has fallen more than a full wavelength behind the other. As the rings become more numerous, the ones caused by very thick layers overlap one another and eventually they combine into white light and no rings are seen.

Note when light travels from a material with lower index of refraction to high index (n) there is a 180° phase change (i.e., destructive). When traveling from high to low index, there is no phase change (i.e. constructive). It might be useful to reference the snaky activity done earlier.

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Sample videos:

<https://youtu.be/IQAk8Md7Wtk?si=YzMO4AZGiCIL3PdC>

https://youtu.be/bQl_Vgqmxko?si=six5T_7WYfVCMvgQ

<https://youtu.be/-ob7foUzXaY?si=KdVA2qQCFhnAcCR6>



Applications of anodization:

When a transparent film is grown to a thickness that is a fraction of the wavelength of visible light (roughly 400 to 700 nm), it creates optical effects like what you see in an oil slick. As light hits the surface of an anodized oxide layer, some of the light reflects off the top of the oxide, while some passes through and reflects off the underlying metal. Depending on the exact thickness of the oxide, these two reflected light waves either add together (constructive interference, making the color brighter) or cancel each other out (destructive interference). Because anodization voltage dictates the exact thickness of the film, changing the voltage changes which colors undergo constructive/destructive interference. The result can be vibrant, iridescent colors on titanium and niobium jewelry or consumer titanium products. On an industrial scale, anodizing specific metals under precise conditions can create specialized oxide layers that eliminate surface reflections (similar to anti-reflective coatings on eyeglasses) or act as high-performance optical filters.

Unlike paint or conventional plating (which just coats the outside), an anodized layer is **grown entirely from the base metal itself**. Anodization doesn't chemically change the dye molecules themselves, it just traps them inside the porous oxide structure. In the case of titanium, it creates colors through physics (light interference) rather than pigments. This means it becomes fully integrated into the substrate and will never chip, flake, or peel. Anodization is an electrochemical process used in many industrial applications to transform a metal's surface into a corrosion-resistant finish. The process thickens the naturally occurring oxide layer of a metal that results in a permanent structural alteration to the surface and can last over 50 years.

The anodization process has multiple uses including:

- Laptops, smartphones (e.g., iPhone casings), and smartwatches use colored anodized aluminum for a scratch-resistant, premium metallic finish.
- use of heat sinks, gears, and engine parts which rely on the hard, non-peeling oxide layer for abrasion resistance and heat management.

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- Many portable speakers and headphone components use anodized surfaces for vibrant, fade-resistant color.
- Window frames, storefronts, and roofing systems use anodized aluminum to protect against weather exposure.
- Bathroom accessories and mailboxes use the process to prevent rusting.
- Cookware uses anodization to give durable, non-stick pans that will not react with acidic foods.
- Pistons and hydraulic valves use a heavy-duty anodized coating to reduce friction and prevent wear.
- Aircraft wings use thin anodized layers to protect from extreme weather without heavy weight.
- Camping gear, bike frames, and car wheel rims use anodized finishes to resist rusting.
- Titanium surgical tools and medical implants are anodized to create an inert surface that the human body accepts.

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