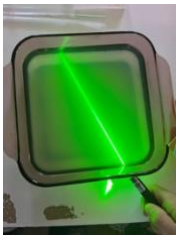
PROPERTIES OF LIGHT
In MEDIA

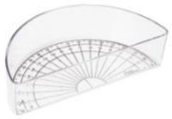
Light interacts with materials in non-intuitive, but predictable ways. When light hits a material, some light may bounce off, and this is called reflection. As light passes through materials, its speed may change, causing objects to appear bent, like a pencil in a glass full of water. This is called 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.
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.

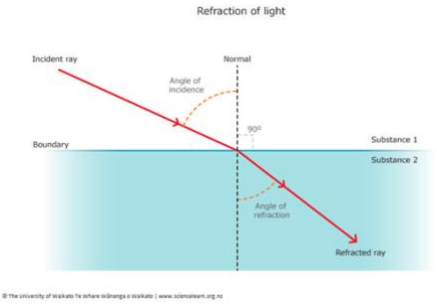
Objective: Students will observe reflection and refraction of light in different media.

Gelatin or Jello Cubes Procedure
Preparing the Gelatin Block:

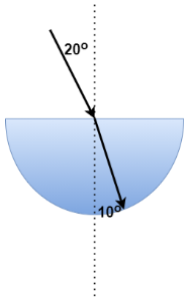
- Mix gelatin powder with warm water according to the instructions. Adding more gelatin (3x as much as in box recipe) is often preferred to reduce chance of liquification during class.
- Pour into a mold (hint: spraying with Pam helps with removal) and let it set in the refrigerator until firm (3-4 hours 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.

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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.
- 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.



DRAFT

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

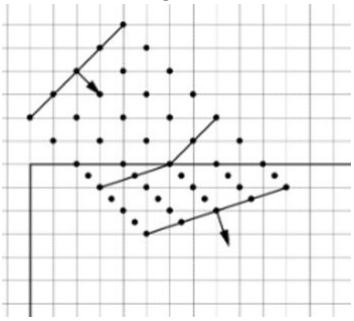
The speed of light is always constant in a vacuum. However, in materials (acrylic, glass, gelatin) light appears to travel slower. This is NOT because photons slow down, but because of how they interact with the material. Light is an electromagnetic wave. When it enters a material, it interacts with 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

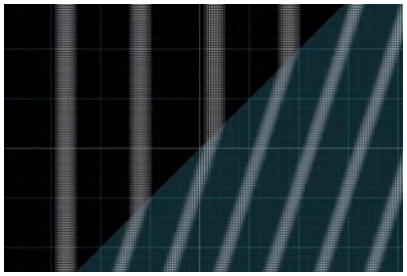
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To help students to conceptually understand why the light will bend while slowing down and not for a medium entering perpendicular to the surface (i.e. along the normal), it may help to use a graph to plot points similar to what is shown. Start with 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=ZaZlqFbzBHRIhHh9

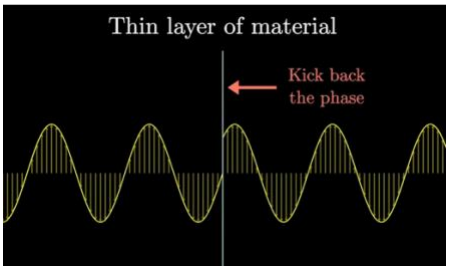
Part 2: 9-11 min. shows oscillations and frequencies (analogy to pushing swing). Higher frequency will cause the charges to wiggle with greater amplitude resulting in higher amplitude EM radiation which creates a bigger phase kick, which shortens the wavelength proportionally more resulting in higher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

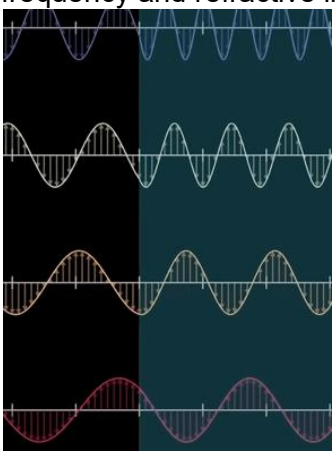


When light travels between different media, its speed (v) and wavelength (λ) change (e.g. decrease), but its frequency (f) remains constant according to the equation $v = f\,\lambda$.
The wavelength within the medium is determined by the frequency and refractive index of the medium.

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

c = speed of light in a vacuum
n= refractive index

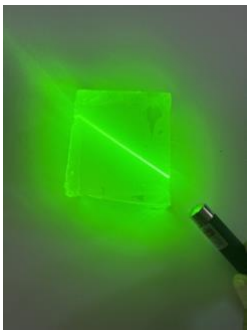
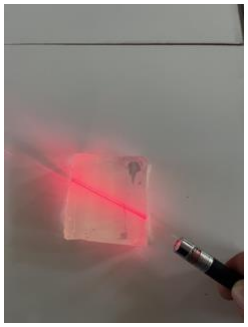




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Summary: Light causes the charges to wiggle, so they create their own EM wave which gives the light a phase kick shortening its wavelength which slows it down. Refraction separates colors because different colors bend differently as they pass through 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/LKI1UmFbfaA?si=sHFQn5pAf3OVn-DU



Discussion questions:

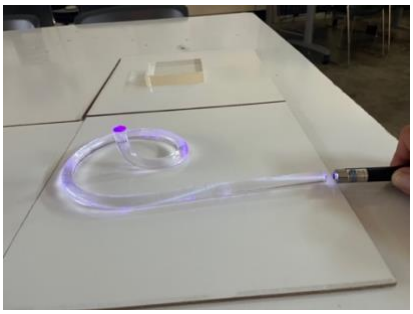
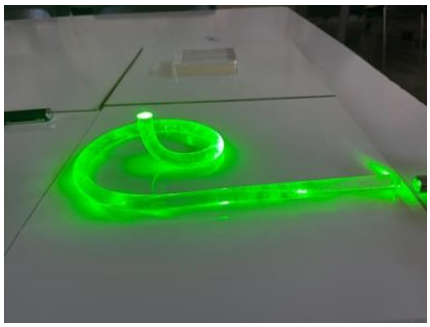
- What happens to light as it passes from air to the gelatin (or acrylic block)? *It slows down and bends toward the normal line.*
- Why does total internal reflection happen only when light travels from gelatin to air (or the acrylic block to air)? *Total internal reflection only happens when light 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*

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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.
- 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

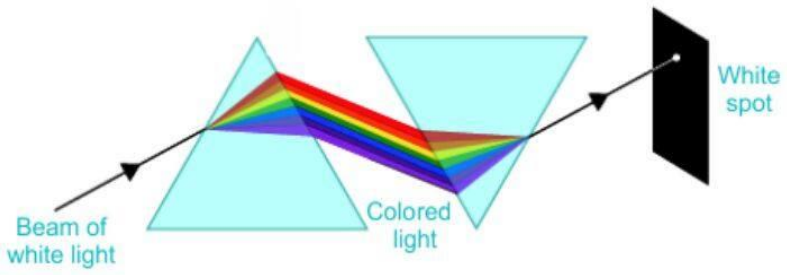
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environment will alter the evanescent wave. Environmental change examples can be the presence of chemicals or pollutants. These changes affect the light's intensity, phase, or polarization, which can be measured. Biosensors, chemical sensors, and environmental 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.



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)

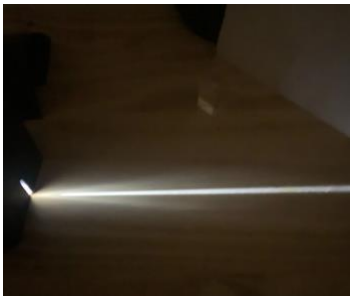


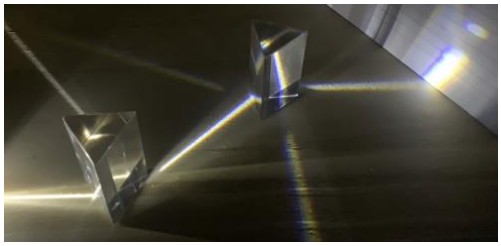
Objectives:
Students will be able to observe the spectrum of white light as it passes through a prism and separates the colors red, orange, yellow, green, blue, and violet (ROYGBIV).
Students will be able to observe how light colors can be recombined back to white light by going back through a second 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.

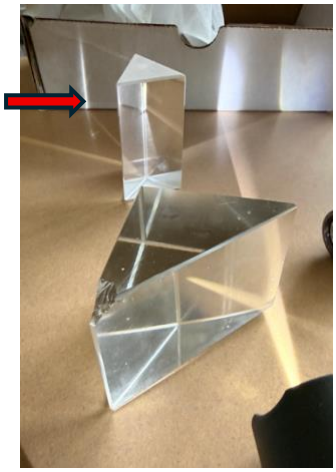


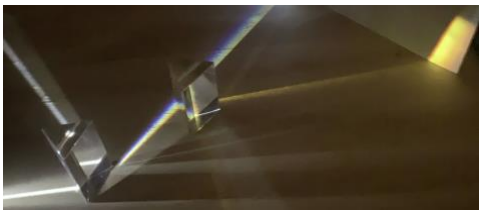
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2. Slide the prism through the individual colors of the spectrum of light. Observe the spectrum produced by the second prism. Next, arrange the first prism so that the entire spectrum passes through the second prism.
3. Carefully place the second prism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

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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.

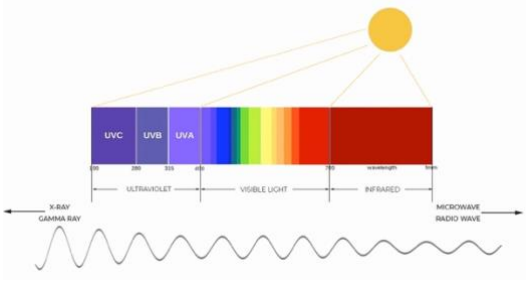
Teacher Notes: It is visually helpful to have the students color the spectrum as many have never noticed the colors are in a specific order. It may be useful to have them predict the order of the colors before they go outside.

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 credit[4]

[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.

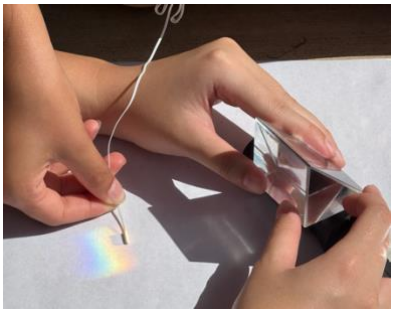


The fact that to the right of the red, beyond of the rainbow, the thermometer still registers a higher temperature can be a mystery to students. When students take the temperature in the shade, it will likely be less than the infrared (IR) reading but will be more than the visible spectrum. The exact 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 that 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 is 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 finished 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:

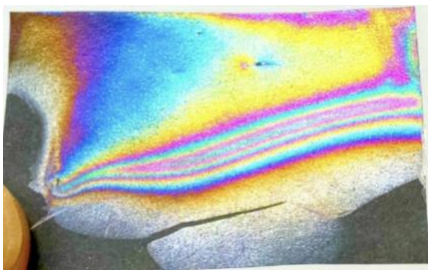
Students are likely familiar with seeing "oil slicks" on the road or water. This is referred to as thin film interference and can be duplicated in many ways including placing a small drop of clearn nail polish on water and then sliding a piece of paper underneath the film to remove it (often called water marbling or rainbow paper). The Nail polish and water do not mix but instead the polish will spread into 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 on 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.



Many students may have used a similar process to create unique patterns on their fingernails. Other resources or videos:
https://carbondalepubliclibrary.org/odd-paints/

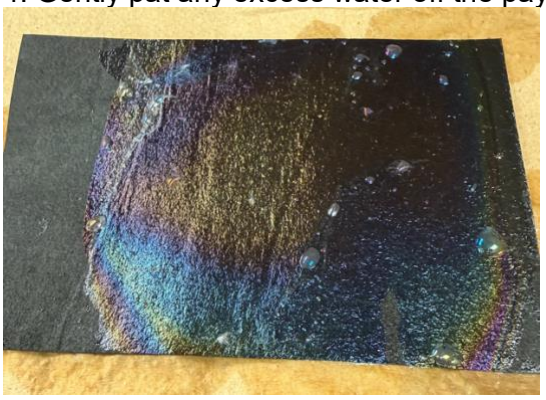
Procedure for Making Rainbow Paper (thin-film interference):

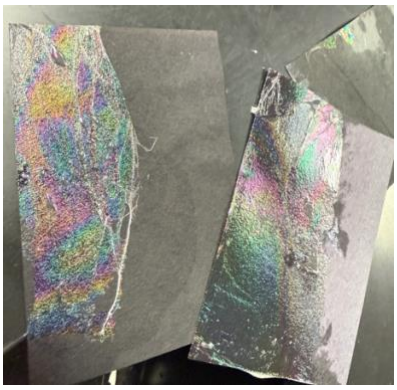
1. Use a shallow bowl or container filled with about 1-2" of water. It is advisable to place the container on a towel or surface that will not be harmed when getting wet as there are usually extra drips of water as the card is removed.
2. Place a single drop of clear nail polish (colored polish will 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 life the paper straight up through the film catching the film on the surface of the paper.
4. Gently pat any excess water off the pay and lay flat on towel to dry.





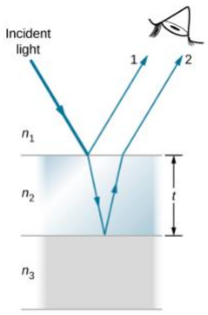
Teacher Background Notes:
When the nail polish spreads across the water, it forms a microscopic film that is only a few hundred nanometers thick. When white light hits this layer, it reflects off both the top of the polish and the bottom of the polish. This is called thin-film interference.

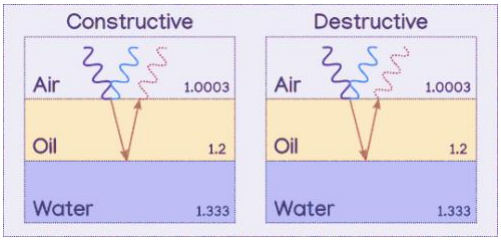
Because the film is so thin, these light waves bounce into each other and interfere (constructively and destructively) and as the paper is rotated, students will notice the colors change. This is due to the light hitting the paper at different angles as it moves and the colors of the rainbow vary with 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 innder 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 180º 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/lQAk8Md7Wtk?si=YzMO4AZGiCIL3PdC
https://youtu.be/bQI_Vgqmxko?si=six5T_7WyfVCMvgO
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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