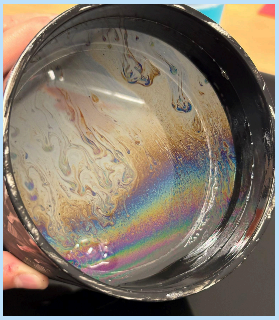
Dragonfly Colours: Thin-Film Interference

SPS SOCK 2024

This demonstration uses a bubble and LED light to illustrate the concept of thin-film interference. It centres a discussion on thin-film interference in dragonflies and asks participants to think about where they see reflection and refraction in their lives.



PRESENTER BRIEF

The presenter should be familiar with introductory optics. An understanding of thin-film interference, reflection, and waves is necessary. Expect to answer questions on the difference between reflection and refraction, and why light behaves in this way.

Number of Participants: 5
Audience: Elementary to High School
Duration: 20 minutes
Difficulty: Level 2

MATERIALS REQUIRED

Demo:
- Bubble solution
  - Dawn dish soap
  - Glycerin
- Shallow tray
- LEDs over 5000K
- Black PVC tube (19 cm diameter)
- Black surface

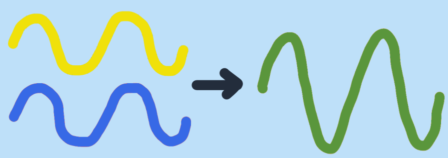
Extension:
- Rubbing alcohol
- Insect wing/shell or bird wing

VOCABULARY

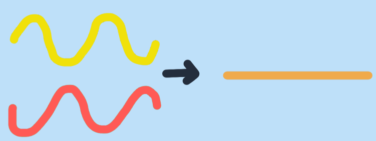
Light: electromagnetic waves that can be perceived by the human eye

Medium: the material waves move through
Source: objects that emit light
Waves: a disturbance or change in physical quantity that transports energy or information from one point to the next

Wavelength: the distance between two peaks of a wave
Phase shift: the difference in the location or timing of two points in a wave
Interference: interaction between waves that can either increase their amplitude (constructive), or decrease their amplitude (destructive)
Reflection: the change in direction of wave propagation when encountering a change in refractive index, so that the wave returns to the medium it originated from
Refraction: bending of a wave when encountering a change in refractive index of the medium
Index of refraction: a characteristic of transparent materials which describes how light propagates through the medium in relation to space
Thin-film interference: a phenomenon when light reflects both above and below a thin layer, allowing for constructive and destructive interference to occur
Constructive interference: when two waves that are in phase add together resulting in a larger amplitude



Destructive interference: when two waves that are out of phase add together resulting in a smaller amplitude



<u>USEFUL EQUATIONS</u>

Law of refraction	$n_i \sin\theta_i = n_r \sin\theta_r$ n is refractive index, θ is incidence angle
Thin-film interference	$2tn = m\lambda$ and $2tn = (m + \frac{1}{2})\lambda$ t is the thickness of the film, n is the index of refraction of the film, m is the integer phase shift, and λ is the wavelength of light on the film

<u>ADDITIONAL RESOURCES</u>

This demo pairs well with *Dragonfly Flight: Waves and Wing Movement* and *Dragonfly Sight: UV Light and Electromagnetic Waves* from SPS SOCK 2024. *Transverse and Longitudinal*

Waves and *Reflection & Refraction* from the SPS Demonstrations website are additional supplements. Digital simulations, such as these three examples, can be used as extension activities for middle and high school students. If groups are larger, have multiple setups and split into small groups.

Some additional resources are:
- Bill Nye refraction clip
- Same-index refraction experiment
- Blue butterfly wing structural colouration
- Structural colouration explainer

Current literature for presenters:
- Dragon colors: the nature and function of Odonata (dragonfly and damselfly) coloration (Suárez-Tovar et al., 2022)

Setup:

Demo:
1. Mix 2/3 cup Dawn dishwashing soap, 2 to 3 tablespoons of glycerine, and one gallon of water. This is your bubble solution.
    a. Ideally, let this mixture stand overnight.
    b. Pre-made bubble solutions can also be used!
2. Pour the bubble solution into a shallow dish.
3. Dip the PVC pipe into the bubble solution.
4. Hold the PVC pipe over a dark surface. Observe the colour patterns.
5. Hold the LED light at different angles over the PVC pipe. Observe and discuss how the patterns change.

Extension:
1. Find a natural object with structural colouration. Some examples may be: bird feathers, butterfly wings, beetle exoskeleton, dragonflies.
2. Drop some rubbing alcohol on top. Watch as the object changes colour as the rubbing alcohol evaporates.

Physics and Explanation:

Elementary (ages 5-10):

The image you see in the mirror is a **reflection**. Light is a **wave** from a **source**, such as a lightbulb in your bathroom. When you see yourself in the mirror, the light starts at the bulb, bounces (or reflects) off of you, reflects again off the mirror, and then finally reaches your eyes. Most objects do not usually emit light, but sources such as the sun, lightbulbs, and lasers do.

Ask students to name sources of lights. How is the light bouncing off objects they are seeing into their eyes?

When light passes from one material to another, such as from air to water, the light waves get bent. We call this **refraction**. Think about sticking your arm in the bathtub or the pool. Your arm looks a little funny in the water compared to how your arm looks in the air. They don't line up completely.

Putting a pencil in a glass of water would work for a visual.

A very thin layer of something, like soap or oil, can be called a film. Light acts a little strangely in a film. Light will reflect off the top of the film, bend a little bit inside it, and then reflect off the bottom of the film. This process changes the light that reaches your eyes, so we see lots of different colours on the film. Some examples of this are bubbles or oil on the pavement. In dragonflies, the very thin layer is different types of exoskeleton. Like the air and water, light travels through and reflects off these layers differently, making dragonflies shine in a rainbow of colours.

Do the demo. Have students hold the LED light at different angles over the PVC pipe. How do the patterns change? A see-think-wonder activity would fit here. The extension activity would be good to do after this. Another option is to ask students to think about what objects they see that show reflection, refraction, or that make rainbows like the bubble.

- Reflection is when light bounces off things, like mirrors.
- Refraction is when light gets bent as it passes through a material.
- Reflection and refraction can change the light waves that reach our eyes.

Middle School (ages 11-13) and general public:

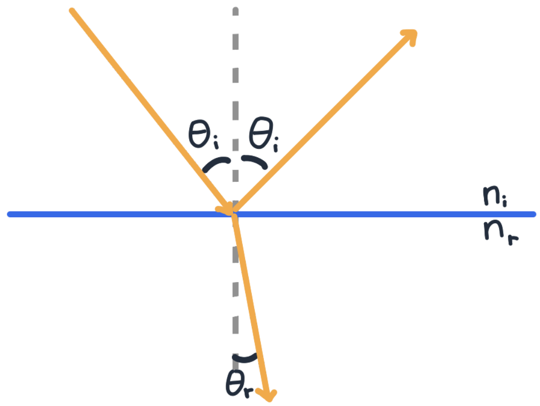
The image you see in the mirror is a **reflection**. Light is a **wave** from a **source**, such as a lightbulb in your bathroom. When you see yourself in the mirror, the light starts at the bulb, bounces (or reflects) off of you, reflects again off the mirror, and then finally reaches your eyes. Most objects do not usually emit light, but sources such as the sun, lightbulbs, and lasers do. In a continuous **medium**, reflected light bounces off a surface at the same angle it hits.

Ask students to name sources of lights. How is the light bouncing off objects they are seeing into their eyes?

When light passes from one medium to another, such as from air to water, the light waves get bent. Think about sticking your arm in the bathtub or the pool. Your arm looks a little funny at the boundary – the part of your arm in the water and the air look segmented and do not line up. This occurs because light waves change speed when travelling through different substances. Materials have a property called the **index of refraction**, which describes how light propagates through a substance. We describe refraction using **the law of refraction:** $n_i \sin \theta_i = n_r \sin \theta_r$.

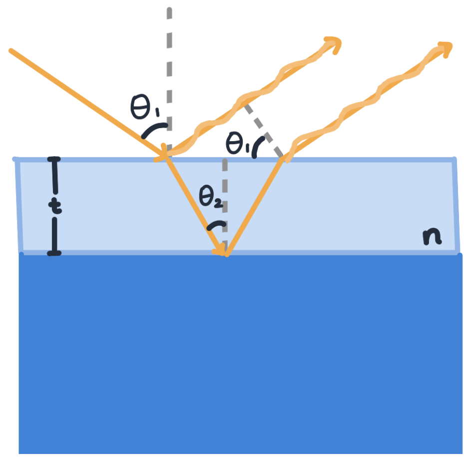
Where n is the index of refraction and θ is the angle the light hits a surface at, relative to 90-degrees. The subscript “i” means these are values for the incident ray, the ray of light that initially strikes the surface. The subscript "r" means these are values for the reflected ray. The law of refraction tells us that the angle light waves hit the material boundary determines the reflection and the refraction angle.

Draw a ray diagram to show how light behaves at a boundary.



At the boundary between mediums, light diverges. Some of it is reflected and some is transmitted into the new medium and refracted. In **thin-film interference**, some light waves reflect off the top surface of a film, and some are transmitted through the film and refract before reflecting off the bottom surface. These waves interfere, and the **constructive and destructive interference** causes colourful patterns. For this to happen, the film needs to be close in thickness to the wavelength of light. When waves reflect off the top surface, there is always a 180˚ **phase shift**. This is a shift of half a wavelength. When they reflect off the bottom surface, the phase shift is a combination of the distance travelled through the film *and* phase shifts introduced by a higher index of refraction. Depending on how the two reflected waves line up, we see either constructive or destructive interference. The colour we see depends on the angle of view because that impacts the distance the light travels through the film–the distance is shorter if you are directly above it and longer if you are at an angle. This changes how the waves of light interfere with each other, resulting in different colours.

Do the demo. Have students hold the LED light at different angles over the PVC pipe. How do the patterns change? Draw a ray diagram to show what is happening to the light. In particular, use it to show how the angle of view changes the distance the light travels through the film.



Thin-film interference is a phenomenon we see in dragonflies. In this situation, we call it a type of **structural colouration**–colour from small structures that interfere with visible light. In structural colouration, only the wavelengths you see are reflected while the others are transmitted through the film. This is in contrast to pigment colour. Pigments absorb all wavelengths of light except the one you see. Structural colours are much more resistant to fading. In dragonflies, parts of their body have layers of cuticles with different refractive indexes. Just like in the bubble, this means we get thin-film interference! Sometimes, this structural colour is combined with pigments to get an even wider variety of hues and iridescence.

Extension activity can be done at this point. If extension activity is done, ask students to hypothesise why this happens. Ideally, have them write down their ideas. Lead this into a discussion of how rubbing alcohol has a different index of refraction than air, and that this changes the thin-film interference that occurs.

- Reflection and refraction describe how light responds to a change in medium.
- We can draw ray diagrams to show the behaviour of light.
- Thin-film interference is a phenomenon where light reflected from the top and bottom of a thin film interfere with each other.

High School (ages 14+):

The image you see in the mirror is a **reflection**. Light is a **wave** from a **source**, such as a lightbulb in your bathroom. When you see yourself in the mirror, the light starts at the bulb, bounces (or reflects) off of you, reflects again off the mirror, and then finally reaches your eyes. Most objects do not usually emit light, but sources such as the sun, lightbulbs, and lasers do. In a continuous **medium**, reflected light bounces off a surface at the same angle it hits.

Ask students to draw diagrams of how light bounces off objects in the room and into their eyes.

When light passes from one medium to another, such as from air to water, the light waves get bent. Think about sticking your arm in the bathtub or the pool. Your arm looks a little funny at the boundary – the part of your arm in the water and the air look segmented and do not line up. This occurs because light waves change speed when travelling through different substances. Materials have a property called the **index of refraction**, which describes how light propagates through a medium in relation to space. We describe refraction using the **law of refraction:** $n_i \sin \theta_i = n_r \sin \theta_r$. Where n is the index of refraction and θ is the angle the light hits a surface at, relative to 90-degrees. The subscript "i" means these are values for the incident ray, the ray of light that initially strikes the surface. The subscript "r" means these are values for the reflected ray. The law of refraction tells us that the angle light waves hit the material boundary determines the reflection and the refraction angle.

Draw a ray diagram to show how light behaves at a boundary. An example is given above.

At the boundary between mediums, light diverges. Some of it is reflected and some is transmitted into the new medium and refracted. In **thin-film interference**, some light waves reflect off the top surface of a film, and some are transmitted through the film and refract before reflecting off the bottom surface.

Draw a ray diagram to show what is happening to the light. An example is shown above.

These waves interfere, and the constructive and destructive interference causes colourful patterns. An important consideration in deciding whether constructive or destructive interference occurs is analysing phase shifts. When waves reflect off surfaces with higher indices of refraction, there is a 180˚ phase shift, or half a wavelength. For **constructive interference** to occur, the two reflected waves have a phase shift of an integer multiple of wavelengths, such as 2 wavelengths, 3 wavelengths, and so on. This shift is a combination of the distance travelled through the film *and* phase shifts introduced by a higher index of refraction. It can be described by the equation: $2tn = m\lambda$. Where "t" is the thickness of the film, "n" is the index of refraction of the film, "m" is the integer phase shift, and "λ" is the wavelength of light on the film. **Destructive interference** occurs when this phase shift is 1/2 wavelength, 3/2 wavelengths, 5/2 wavelengths, and so on. The equation used to describe this is: $2tn = (m + \frac{1}{2})\lambda$.

Do the demo. Have students hold the LED light at different angles over the PVC pipe. How do the patterns change?

The colour we see depends on the angle of view because that impacts how much of the thin film the light travels through to get to your eye–the distance is shorter if you are directly above it and longer if you are at an angle. This distance changes how the waves of light interfere with each other, resulting in different colours.

Refer back to the ray diagram. Use it to show how the angle of view changes the distance the light travels through the film.

Thin-film interference is a phenomenon we see in dragonflies. In this situation, we call it a type of **structural colouration**–colour from small structures that interfere with visible light. In structural colouration, only the wavelengths you see are reflected. All other wavelengths are transmitted through the film. Structural colouration is in contrast to pigment colour. Pigments absorb all wavelengths of light except the one you see. Structural colours are much more resistant to fading. In dragonflies, parts of their body have layers of cuticles with different refractive indexes. Just like in the bubble, this means we get thin-film interference! Sometimes, this structural colour is combined with pigments to get an even wider variety of hues and iridescence.

Extension activity can be done at this point. If extension activity is done, ask students to hypothesise why this happens. Ideally, have them write down their ideas. Lead this into a discussion of how rubbing alcohol has a different index of refraction than air, and that this changes the thin-film interference that occurs.

- Reflection and refraction describe how light responds to a change in medium, we can use the law of refraction to determine how the angle of light changes.
- We can draw ray diagrams to show the behaviour of light.
- Thin-film interference is a phenomenon where light reflected from the top and bottom of a thin film interfere with each other; we can use equations to relate the wavelength, phase shift, and thickness of the film.