Optics in a Fish Tank

Demonstrations for the Classroom

Introduction: This series of demonstrations will illustrate a number of optical phenomena. Using different light sources and a tank of water, you will be able to introduce Wavelengths and color, Rayleigh scattering (why is the sky blue?), Reflection, Refraction, and Total Internal Reflection (TIR).

Equipment required:

1. 5 gallon aquarium (or clear acrylic or glass tank)
   - We recommend a 4" deep Plastic Shotgun Pan manufactured by Cambro ($10.95) purchased from Rochester Store Fixture, 707 North St. (585-546-6706). (Due to the texture of the bottom surface of this vessel, we added a mirror to improve the reflections for the TIR demonstration)
2. High quality flashlight
   - Mag-light style flashlights work the best
3. 5mW HeNe laser
   - Laser pointers will also work
4. Ruler
5. Eye dropper
6. Stands to hold laser and flashlight
7. Catch basin (preferably clear)
8. Milk or dye
9. Water
10. Sponges and rags
    - This could get a little messy!

Brief Introduction to Lasers

Working in a darkened room, begin by pointing out that the laser beam is monochromatic, or made up of one color. The wavelength of the light determines the color we perceive. For a red helium-neon (HeNe) laser, the wavelength is 632.8 nanometers (nm). Red laser pointers typically emit at wavelengths of 635 or 650 nm. This represents a small part of the visible spectrum. Explain that the human eye can detect wavelengths ranging from about 400nm (violet) to 700nm (red).

Be sure to caution the students not to look into a laser.

Point out that the light from the laser is directed. This means it travels in one direction and cannot be seen from angles away from its direction of propagation. The light is there, but unless there is something reflecting it, we cannot see it. Compare the laser light to the flashlight by shining them at a distant wall. The laser spot will be very small compared to the area illuminated by the flashlight.

Direction & Scattering

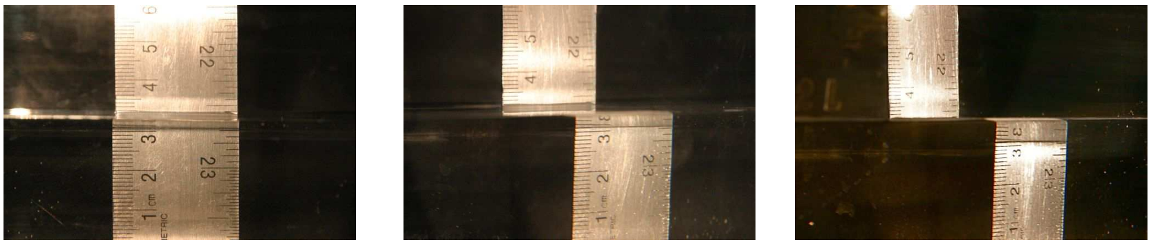
To show how the light beams are directed, it is useful to introduce some chalk dust or other particulate to the beam path. The light scattered by the dust will show the beam's path. Explain that the dust is reflecting some of the light in the direction of our eyes, allowing us to see it.

Next, position the laser to shine through the water-filled tank from one end to the other. Ask your audience if they can see the beam. They should say no, but often there are impurities in the water that allow it to be seen. (Especially if their eyes have adjusted to the darkened room.)

To make the beam visible, use an eyedropper to add 10 drops of skim milk to 1 gallon of water. Stir the water to disperse the milk and the beam should become very visible. Be frugal with how much milk you add, since too much will totally scatter the beam instead of just making it visible. Ask the audience why they can see the beam now. Explain that the milk in the water is doing what the chalk dust did in the air, reflecting a small portion of the light in the direction of our eyes, enabling us to see it.

Refraction

Now place the laser on a stand so that it can be directed down toward the surface of the water at an angle to normal incidence. Use the ruler to show normal and the angles of the incident and refracted ray. Ask the students if they can see that the laser beam changes direction at the surface of the water. Explain that the light changes direction because it slows down as it enters the water. For more advanced students, this is a good opportunity to discuss *index of refraction* and *Snell's law*. (see Vocabulary section) To help motivate the students, ask if they have ever noticed this phenomenon. If there is no response ask if they have ever looked at an object under water and misjudged the object's location. You can illustrate this by holding a ruler upright in the water and looking at it from various angles across the front of the tank. As you move across the front of the tank, the part of the ruler in the water appears displaced by a distance that varies as a function of the viewing angle. At *normal incidence*, the ruler appears straight. The farther you move to the left or right, the more offset the ruler appears. See figure 1.



Normal incidence   25º to the left   50º to the left

Figure 1

Reflection

For reflection, you can show that there is some light bouncing off the bottom of the tank. The angle at which the light is reflected with respect to normal is the same angle as that at which it strikes. The law of reflection states that the angle of reflection equals the angle of incidence, with respect to normal. You can again use the ruler to show *normal* (perpendicular) to the bottom of the tank at the point of reflection. The reflected ray then strikes the surface of the water and refracts. You should be able to see the spot where the beam strikes the classroom wall or ceiling. You may also be able to see some of the light reflecting off the surface of the water and heading back down into the tank. This effect will be maximized in the next step, total internal reflection.

Total internal reflection

Total internal reflection (TIR) occurs when light originating in the medium of the greater index (in this case, water) hits the interface at an angle greater than the critical angle, which is about 48.8º. This demonstration works best with one half gallon of water with five drops of milk. Set up the system so that the laser is angled downward once again, but this time it should hit below the water line through one end of the tank. (See figure 2) You should be able to observe the laser beam bouncing up and down from the bottom of the tank to the surface. The beam will ultimately emerge from the far end of the tank. The number of bounces the laser beam makes depends on the angle of the laser to the normal of the tank's end, the size of the tank, and the water level. If you enter the tank above the water line, TIR will not occur.

TIR explains how optical fibers work. Many students have heard about optical fibers, but they have a hard time understanding what is involved in such devices. The optical fish tank provides a simple method of demonstrating the concept. The next experiment takes this illustration even farther.

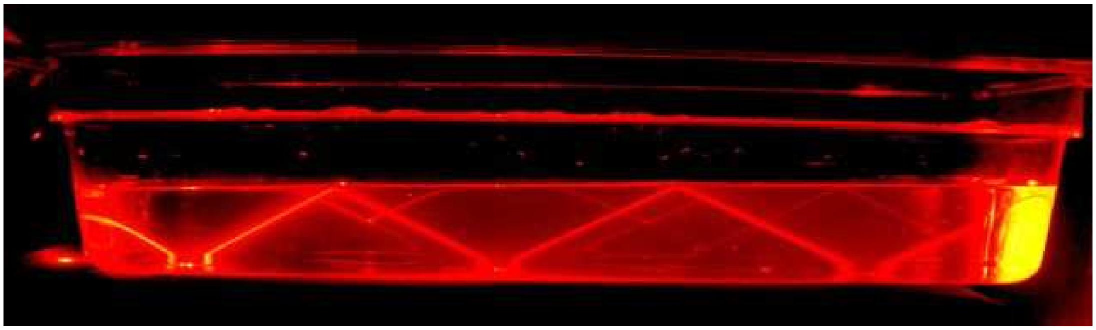


Figure 2

Total Internal Reflection: The Luminous Fountain

For this demonstration, you will need two containers. The first one is the acrylic tank with a ½" diameter hole drilled in one end. The second is a catch basin and can be any standard tank or container that will hold water. This works best if the catch basin is clear. For this demonstration, we used one gallon of water with 10 drops of skim milk. This seems to be a good ratio to show the beam path. If you have a larger tank, use more water, maintaining the same milk to water ratio. The additional water just prolongs the demonstration.

Set up the system as shown in figure 3. Center the laser beam on the hole in the acrylic tank. Use vinyl tape to cover the hole and fill the tank with the water and milk mixture.

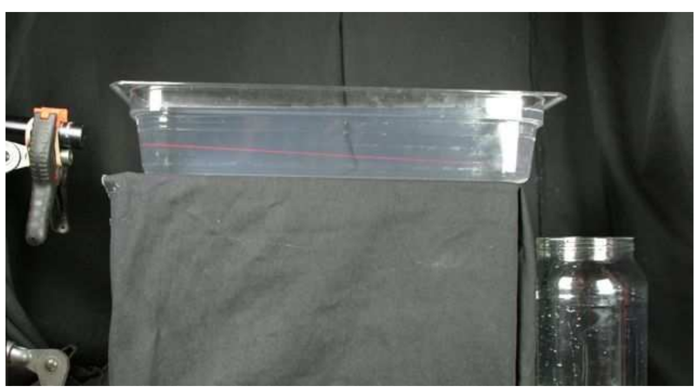


Figure 3

Once everything is set up, the laser turned on, and the lights turned off, unplug the hole and allow the stream of water to flow into a catch basin placed on the desk or floor. (It should be visible to the whole class.) Ask your audience to explain what they see.

The laser beam will be confined to the stream of water by total internal reflection. The stream of water is not typically smooth but we were able to see the beam through several internal reflections. (see figure 4) This little experiment should get many oohs and aahs, since everyone can see that the stream of water is glowing. If the catch basin is clear, you will be able to show nice scattering effects. The water in the catch basin will glow red due to turbulence, air bubbles, and suspended milk particles, making for a visually spectacular presentation.

Figure 4

Rayleigh scattering: Why is the Sky Blue?

One of the most frequently asked questions of all time has to be "Why is the sky blue?" Using your tank full of water and a few drops of milk, you can demonstrate Rayleigh scattering. This is the scattering of electro-magnetic radiation by small particles in a gas or liquid. The visible spectrum represents a small portion of the electro-magnetic spectrum. What we perceive as white light is a combination of all visible wavelengths. The difference between the different colors, on a physical level, is that the different colors have different wavelengths and frequencies. The blue end of the spectrum has the highest frequency and the red end has the lowest frequency. The shorter wavelength blue light is more readily scattered by the atmosphere than the longer wavelength red. This scattering directs the blue waves to our eyes and makes the sky appear blue.

This can be demonstrated by shining a bright flashlight into the end of the tank of water with a small amount of milk. The blue light waves will be scattered and the tank will take on a faint blue tinge. Using a long tank, you can show the effect that causes the sky to appear orange at sunset.

As you increase the amount of milk in the water to 25 to 30 drops, more of the short wavelengths are scattered as they pass through the tank. As more of the blue light is scattered, the longer red waves continue and the water at the far end of the tank will begin to have an orange tinge.

Explain that as the sun gets lower in the sky, the distance it travels through the atmosphere increases. The longer orange and red wavelengths are not scattered as much by the atmosphere and continue to travel in the direction of our eyes. This is why the sun appears red and the sky takes on an orange color as the sun sets.

Vocabulary

Helium-neon (HeNe) laser – The most commonly used gas laser. The HeNe laser has an emission that is determined by neon atoms by virtue of a resonant transfer of excitation of helium. It operates continuously in the red, infrared and far-infrared regions and emits highly monochromatic radiation.

Normal – An axis that forms right angles with a surface or with other lines. The normal is used to determine incident, reflective and refractive angles.

Normal incidence – Light striking a surface at an angle perpendicular to the surface.

Angle of incidence – The angle formed between a ray of light striking a surface and the normal to that surface at the point of incidence.

Index of refraction – The ratio of the velocity of light in a vacuum to the velocity of light in a refractive material for a given wavelength. Usually represented by the letter n.

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

n represents index of refraction, c is the constant speed of light in a vacuum, and v is the velocity of light in the refractive material.

Snell's law – Snell's law is a formula used to describe the relationship between the angles of incidence and refraction, when light travels through the boundary between two media that have different indices of refraction. The formula states:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 \ .$$

Where n_1 is the index of refraction of the first medium, θ_1 is the angle between the incident ray and normal to the surface at the point of incidence, n_2 is the index of refraction of the second medium, and θ_2 is the angle between the refracted ray and normal to the surface at the point of incidence. This formula is used in optical ray tracing to predict the direction light will travel when it passes into a material of different refractive index.

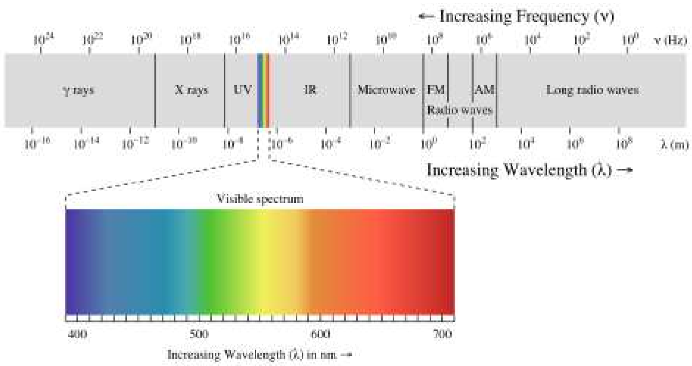
Total internal reflection (TIR) – The reflection that occurs within a substance because the angle of incidence of the light striking the boundary surface is in excess of the critical angle.

Critical angle – The least angle of incidence at which total internal reflection takes place. The angle of incidence in a denser medium, at an interface between the denser and less dense medium, at which the light is refracted along the interface. When the critical angle is exceeded, the light is totally reflected back into the denser medium. The critical angle varies with the indices of refraction of the two media with the relationship:

$$\text{Sin } I_c = \frac{n'}{n}$$

Where I_c is the critical angle; *n'* the refractive index of the less dense medium, and *n* the refractive index of the denser medium.

Electromagnetic spectrum – The full range of electromagnetic radiation, from the shortest gamma rays to long radio waves. It includes X rays, UV, a very narrow visible spectrum that we think of as light, infrared radiation, microwaves, and radio waves.



Rayleigh scattering – Scattering by particles very small compared with the wavelength of the radiation being considered. In the visible region of the spectrum, blue light is scattered more strongly by the molecules of the air than longer wavelengths, accounting for the blue color of the sky.

References:

Demonstrations suggested by a series of articles Optics for the Fish – Parts I & II by R. John Koshel. Published in Optics & Photonics News, April & May 1998.

Vocabulary definitions were taken from The Photonics Dictionary 2007, and Wikipedia.

Photos by Mike Spryn, Optimax Systems, Inc.