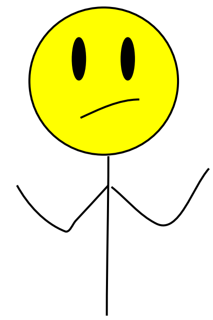
Boring: What Optics Isn't, And How I Got There

By S Chen, 7th grade, CA



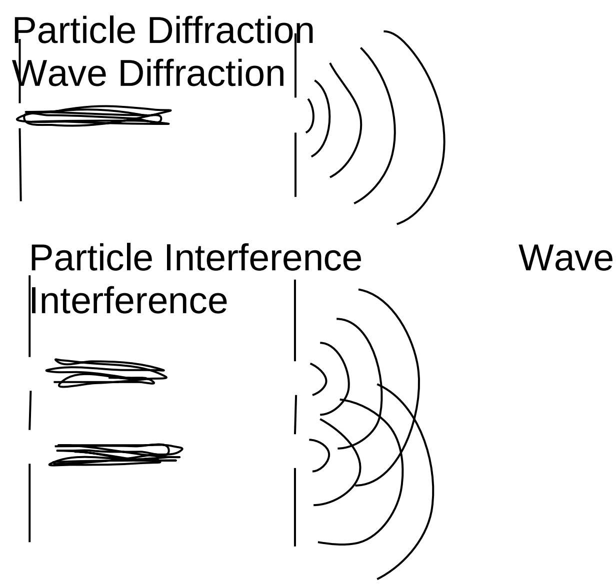
When I first started this course, I thought it would be easy. Possibly boring, even. My science class at school (and it was pretty hands-on!) had gone over some of it. I had read books about it. I thought I knew it all, and there was nothing left to learn**. Oh, how wrong I was.**

I already knew that concave mirrors and convex lenses converge light, and convex mirrors and concave lenses diverge it. I had traced light rays through lenses. Mirrors seemed to reverse left and right. Colors came from different wavelengths (though I didn't know it was not accurate). Light was both a particle and a wave: photons and light rays. Nothing could go faster than light in a vacuum, and it slowed down in other mediums. A prism separated different wavelengths of light. Rainbows came from refracted light in water droplets. The sky was blue because of Rayleigh scattering (though I had no idea what that was). Telescopes and microscopes use lenses. The primary colors of light were red, green, and blue. Ink reversed them: magenta, yellow, and cyan. Stars twinkle because the atmosphere is in the way. Light always travels in a straight line. It changes direction through a different medium. I knew all that. I had books and a teacher to tell me all of that. I didn't expect that there would be more to learn, more to wrap my head around. I heard that photons had no mass (though I didn't know photons just don't have static mass and what it means). I knew omputer colors came from RGB: certain colors can be "created" using different amounts of red, green, and blue (though I didn't know they only work for human eyes and why. I also didn't know how are they different from the "real color" in the rainbow). I had never even thought about "one-way mirror glass" at all, or why things sparkled.

Right away, from lesson 1, I was proved wrong. Lesson 01A gave me no special interest, but starting from 01B I was intrigued. I attempted to devise a formula for the number of virtual images formed with a pair of mirrors at a certain angle. I explored the world of pinhole images and got mad at aluminum foil. In lesson 01C, I pondered the ways to reflect a light ray exactly backwards. In lesson 01D, I gawked at the seemingly holographic spring and strawberry and tried to explain it. In lesson 2, I fiddled around with lenses, found Snell's Law through my own experiments, understood mirages, and explored various magic tricks. In lesson 3, I discovered many mathematical relationships for concave and convex lenses, found how to make fire with ice, and figured out how movie projectors, cameras, and eyes work. But it was lessons 4 and 5 that sparked my curiosity the most.

Even before I started lessons 4 and 5, I had done a lot and explored a lot, including finding my longitude and latitude with surprising accuracy. I had lots of fun, performed lots of experiments, and learned lots of information. However, ray optics wasn't the most interesting part. Tracing light rays was fun, but it wasn't as challenging as the second half of the course.

An interesting non-optics question that was proposed was whether something was both rectangular and round. And indeed there is: from different angles, a cylinder is both rectangular and round. That was not what I proposed, and my idea was rather silly: a rectangle with a circular hole. In fact, that is neither. I had no idea this question is the foreshadowing for the next couple of lessons: what light is?



In lesson 4, I enthusiastically watched the battle between theories of light: particle or wave theory. I already knew who would win, but seeing why and how light really was a wave was much more fun and illuminating than merely knowing the result. Both the particle and the wave theories supported dispersion: different particles and different wavelengths. Both the particle and the wave theories supported the straight-line property and the law of reflection: the particles being perfect and the secondary wavefronts actually forming the line. Both the particle and the wave theories may explain polarization: if the particles are ellipsoids (which raises questions about the perfect elasticity of the particle) but the waves can oscillate in different directions. However, only the wave theory can explain diffraction and interference. The deciding factor came to the speed of light in other mediums. To explain how light changes directions at the boundary between two media, the particle theory suggested that the gravity of a denser material speeded up the light, while the wave theory proposed that the wavefronts were closer together in denser mediums and that light was slower. In fact, light is a wave. The speed of light is found to be slower in water than in air many years after this debate started.

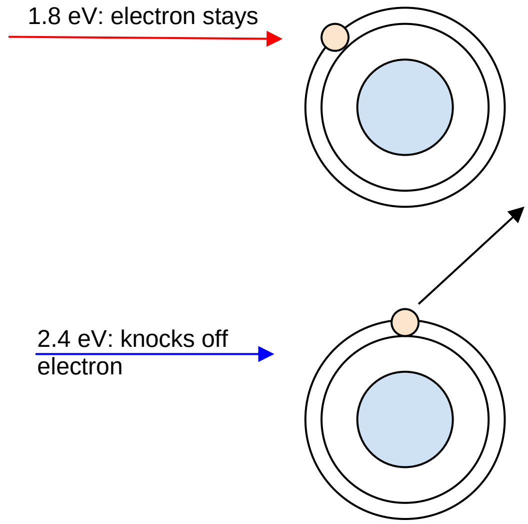
What indeed is a wave? A wave is a propagating dynamic disturbance of one or more quantities. A transverse wave oscillates perpendicular to the direction of propagation, while in a longitudinal wave they are in the same direction. Wavelength is the distance from crest to crest or trough to trough. Frequency is how often the wave oscillation occurs in a set period of time. The period is how long it takes to travel one wavelength. The wavelength and frequency are inversely proportional.

However, there were still two dark clouds hiding the truth about light which contradicted the wave. What is light's medium if it is a wave (it travels through space: luminiferous ether?) and why can blue light release an electron from an atom while red light cannot (the photoelectric effect)? The answer to those, I had absolutely no idea.

Of course, suspense is key to exciting discoveries, and suspense there was! Only towards the end of lesson 4 was the truth revealed, and boy was it exciting!

It was not known how light could travel through vacuums if it were not particles: all waves seemed to need mediums to propagate. The proposed solution was that space was filled with luminiferous ether, but that was proved not to exist experimentally! Turns out, light is a special kind of wave: an electromagnetic wave, just like infrared, x-rays, gamma rays, radio waves, and ultraviolet rays. Electromagnetic waves can travel through vacuums because the changing electric field causes a change in the magnetic field and the changing magnetic field causes a change in the electric field. When one is changed, both fields continue changing forever because of the mutual changes. No medium is needed for electric waves or magnetic waves, and this kind of wave has sparked an entirely different branch of physics: electromagnetism. Of course, since we were taking an optics course and not electromagnetism, we didn't learn too much about electromagnetism, but we learned enough to blow away the other dark cloud.

The photoelectric effect's solution was in fact that light is also particles, but not the particle in the way Newton described it. This type of particle, a photon, has no static mass (so it's not exactly like matter) but has energy. A photon is indeed the smallest package of light energy, which can not be further divided. All electromagnetic rays are also photons, and higher frequencies meant higher photon energy. If the energy was over 2.0 eV, that meant it could knock an electron off of a particular atom from a particular energy lever, turning it into an ion. Red light has a photon energy of 1.8 eV, blue light 2.4 eV, and violet light 3.1 eV. That's why different colors behave differently in the photoelectric effect. Ultraviolet light, x-rays, and gamma rays are especially harmful because they have high photon energies and can knock off electrons quickly and easily.

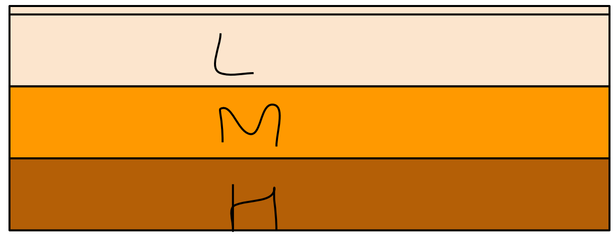


This particle-wave duality is not uncommon. In fact, electrons can also be waves and all electromagnetic waves have this property. Finally, I realized why we were asked what is both a circle and a rectangle!

The dark cloud reveals weren't the only things in lesson 4C: thin-film interference was extremely interesting as well. What film counts as thin? Thin film is comparable to the wavelength of light: only hundreds of nanometers in width. We found it from experimental photos of thin-film interference and Newton's rings that there was the *half-wave shift*, which only occurred in certain cases, not in all thin-film interference. Only when going from a low-index medium to a high-index medium is there a half-wave shift. There is no half-wave shift from high-index to low-index.

In the case where a high-index medium is sandwiched between two low-index mediums (same index of refraction for the "bread"), there is only one half-wave shift, so bright spots are at $2dn_2 = (m + \frac{1}{2})\lambda_0$ where λ_0 is the wavelength in a vacuum, *d* is the thickness, and n_2 is the index of the high-index medium. *m* can be any nonnegative integer. The dark spots of reflection appear at $2dn_2 = m\lambda_0$ in this case.

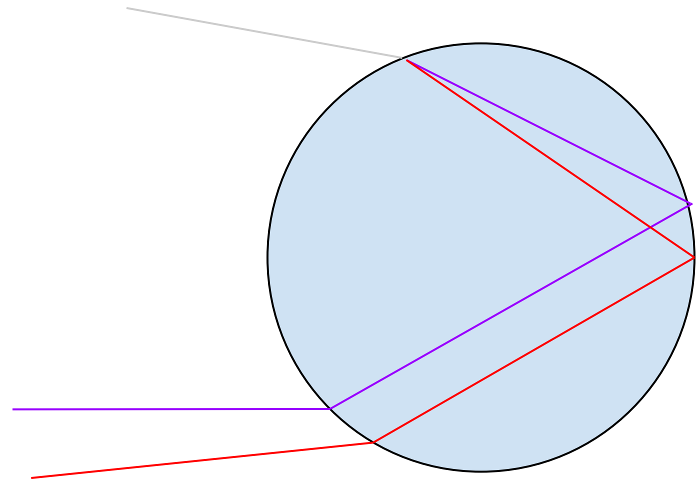
When it is low-index to medium-index to high-index, it's different. There are two half-wave shifts and the light spots are therefore at $2dn_2 = m\lambda_0$ and the dark condition in reflection is $2dn_2 = (m + \frac{1}{2})\lambda_0$. This is used in thin-film coating to reduce reflection and enhance transmission through lenses.



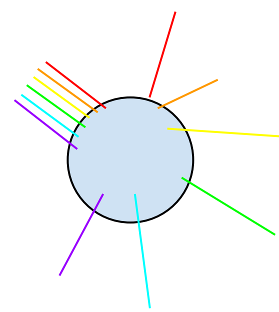
It turns out that visible light microscopes cannot show details smaller than the wavelength of visible light: if it is too small, light diffracts dramatically without going along straight lines anymore. The ray optics imaging theory is no longer applicable. For that, an electron microscope is needed. Because the wavelength of electrons can be thousands of times shorter than that of visible light, the resolution of an electron microscope can be thousands of times better than that of a visible light microscope. The things of atom or electron sizes are in the reach of quantum mechanics. The wave-like properties of an electron are used here.

In lesson 5 we shifted from waves and interference to color. When monochromatic light illuminates something, we get little information about the "color" or the object. All we can find is how intense that color of light is in reflected in certain spots. Different lamps can also emit lights of different parts of the spectrum to make the same image look different. But it is not the wavelength of light that determines the color: it is the frequency. For example, when red light enters water from air, it is still red, the frequency doesn't change but the wavelength reduces by 1.33 times.

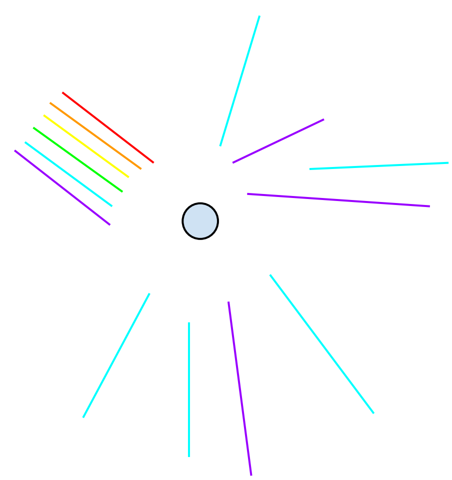
The reason that prisms can separate colors is that different frequencies of light are refracted slightly differently. Violet light is bent slightly more severely than red light. The triangular shape bends the light rays in the same direction twice, making the separation more obvious. In a rainbow, water droplets act as prisms, with the pattern of refracting (air to water), reflecting (water to water), and refracting (water to air). Finally, violet light is refracted 42° while red light is refracted 40˚, through a spherical water drop. The second rainbow is formed when there is one more reflection-and-refraction before the light rays leave the water droplet. When I used a spray bottle to create a rainbow and it worked, I practically squealed with delight. (Yes, I like rainbows.) I repeated it just for the fun of seeing the rainbow.



But then, if ice and sheets of glass are transparent, why are frost, snow, and crushed glass white? The answer is Mie scattering, which applies to things similar to the wavelength of light: between 0.1 and 10 microns. Powdered glass, water vapor, aerosols, fat globules in milk, and smog are all in this category. This is why clouds are white and the sky can be white when the air is not clean.



When the air is clean and the sun is shining, the sky is blue because of Rayleigh scattering. I mentioned that I, before taking this course, had absolutely no idea what Rayleigh scattering was, simply accepting that it was the reason that the sky was blue. Rayleigh scattering is due to particles (such as air molecules) way much smaller than the wavelength of light, hence it affects blue and violet much more than red and orange, so the sky should be a rich blue-violet; however, our eyes do not detect violet readily so the sky is blue. To birds, who can see ultraviolet light, the sky would be violently violet. Sunsets are red-orange because the light rays in the direction of the horizon need to travel farther in the air before reaching us.



Combining light is different from combining paints. Paints are made to absorb color, and light source is made to emit. To human eyes, red light and green light make yellow light, red and blue make magenta, and green and blue make cyan. This is the principle behind inks: magenta ink absorbs green, yellow ink absorbs blue, and cyan ink absorbs red. The reason that red and green light combined in the right proportions looks like different shades of yellow is that we have only three kinds of cone cells to detect three groups of light frequencies. We can't tell the difference between the red-plus-green light and pure yellow light. Our brains combine different amounts of these three groups and interpret it as one new color, so a computer only needs to emit red, green, and blue light to create a plethora of colors. Pink is formed by combining various shades of red, green, and blue.

All electromagnetic waves travel at the same speed in the air, so a simple cheese experiment using a microwave oven could find the speed of light. The frequency of the microwave times twice the distance between nodes (bright/dull spots, which is half the wavelength) would give the speed of microwaves and therefore the speed of light. If the rotating stand were taken out, the nodes would be easily seen by the meltiest cheese.

Other animals don't have the same cone cells as we do. Birds have the addition of ultraviolet cone cells, and many insects can see ultraviolet but not red. Dogs cannot tell the difference between red and green. Colorblind people cannot tell the difference between certain colors because one or more of their cone cells is deficient or deactivated.

Optics is beautiful and complicated. Optics is interesting and possibly dangerous, as in the case of the sun or a laser. Optics is the study of light. What is light? Light is an electromagnetic wave of a certain range of frequencies. Light is both a particle and a wave. Light allows us to perceive the world around us. Light is an important part of our lives. Now, I ask others to answer this question for themselves: what is light, and what does it mean to you? Isn't optics wonderful?