Light as waves

Lights have different colors. For example, some lights are blue, and some lights are red. So, why are they different? Actually, light is a wave, and its wavelength determines the color. Another example of a wave is sound. Its wavelength determines its pitch, such as ``Do,'' ``Re,'' and ``Mi.'' Of course, to understand what I mean, you need to understand what a wavelength is.

I am sure that you have heard of the word "wave." A wave travels and has a wavelength and an amplitude.[1] See Fig. 1 for a schematic drawing of a wave, and see Fig. 2 to see how it is traveling. If you think about a water wave, such as the one you see on the beach, or such as the one you can make on a pond by dropping a stone, you will understand what I mean by Fig. 1 and Fig. 2. In Fig. 1, λ (pronounced as "lambda") is the wavelength, and A is the amplitude. Here, the y-axis denotes what is called "displacement." You see that the amplitude A is given by the maximum displacement. The bigger the amplitude is, the more intense a wave is. On the other hand, if there is no wave at all, the amplitude will be zero, and the displacement will also be given by zero at every position. The dotted graph in Fig. 2 shows the wave after traveling the distance of Δx. However, there are waves that are not manifestly visible like water waves. Good examples are sound waves and light, which is an electromagnetic wave (i.e., the wave of electromagnetic fields.)[2] In such cases, you don't actually see a picture like Fig. 1, but we can still talk about their wavelengths and amplitudes. In the case of sound waves, the displacement is given by the position of air molecules deviating from their original, equilibrium position (i.e., when there is no sound).

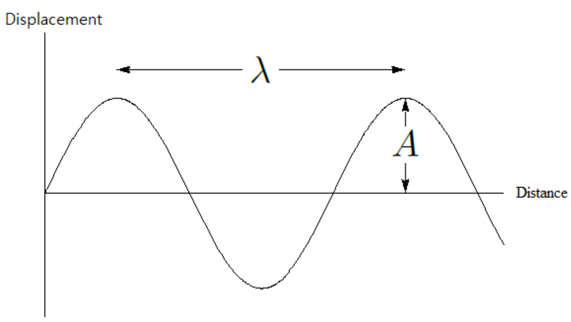

Fig. 1: a wave

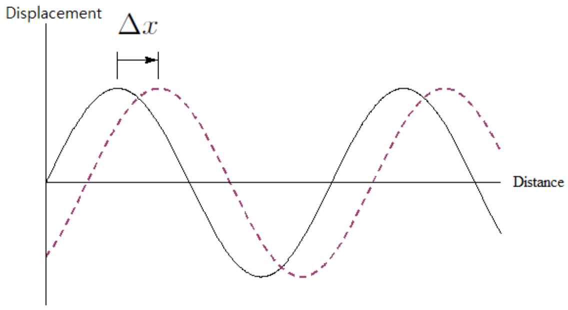

Fig. 2: a moving wave

Now, I would like to point out a common misconception about waves. If you drop a stone on a pond, you see that the wave propagates from the point on which you drop the stone. So, you may

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[1] Strictly speaking, there is a wave called "standing wave" which doesn't travel, but at the moment it is better to think that a wave always travels. We will talk about it later.

[2] A field is an abstract concept that permeates through space. We will learn about it later. We will first encounter an example of a field in our later article "Magnetic field."

naively think that actual water molecules are propagating in the direction the wave is propagating. No, they aren't. They are just oscillating up and down. The same can be said about other waves, such as sound waves. The actual air molecules are not propagated when sound waves are propagated. They just oscillate around their original positions. Think about it this way. See Fig. 3. Suppose you grab an endpoint of a rope and move it up and down. The actual rope doesn't move rightwards, which is the actual propagating direction of the wave, but it only moves up and down at each point.

Now, let's return to Fig. 2. Let's imagine the case in which Δx is not the one drawn on the figure, but λ, the wavelength. Then, it is easy to see that after traveling by the distance of wavelength, the wave returns to its original form. The time it took so is called "period," usually denoted by T. Another viewpoint of the period is that it's time a point on the wave takes oscillating once up and down and returns to its original position.

Fig. 3: shaking a rope to make a wave going rightward

Another convenient value that can describe a wave is "frequency" usually denoted by "f." The unit for frequency is called "Hertz" (denoted as "Hz"). It's the number of oscillations per second. For example, if a wave oscillates 100 times a second, its frequency is 100 Hz. This also means that the period is 0.01 seconds. This implies

$$T = 1/f \qquad \text{i.e.,} \qquad f = 1/T \tag{1}$$

In any case, if you like listening to the radio, you may be familiar with Hertz. If your favorite channel is 95 MHz (pronounced "Mega-Hertz"), it means that the frequency of the radio wave which your favorite radio station is sending is 95,000,000 Hz. (1 Mega corresponds to 1 million).

Now, let's find a relation among the speed of a wave, its wavelength, and its frequency. First, the speed of a wave is given by

$$v = \lambda/T \tag{2}$$

because, during a period, the wave travels by the distance of the wavelength. So, combing (1) and (2), we obtain

$$v = \lambda f \tag{3}$$

Now, let's talk about light. We already mentioned that light with different wavelengths has different colors. Then, what wavelength would colorless (i.e., white) light have? In the 17th century, the English mathematician and physicist, Sir Isaac Newton found out that white light is a mixture of light of all colors. An example of white light is the sunlight. He passed the sunlight through a prism and found out that the prism spreads the sunlight into the light of different colors. See Fig. 4 for a photo of a prism that does so. Well, this is nothing new. He was not the first one who discovered that a prism spreads light into different colors. However, when he picked a ray with one color, say blue, and passed it through a second prism, he found out that the second prism did not further spread the blue ray into many different bluish colors, but it stayed purely blue. Before Newton's time, people naively believed that prism "adds" color into the light. What Newton showed was that prism "separates" light according to its color (i.e., wavelength). Once the sunlight is separated so, the second prism cannot do anything further, because the light is already separated to light with each color. He performed another experiment. This time, instead of passing only one ray through the second prism, he used the second prism to combine all the light of different colors. Then, he found out that they became white light again!

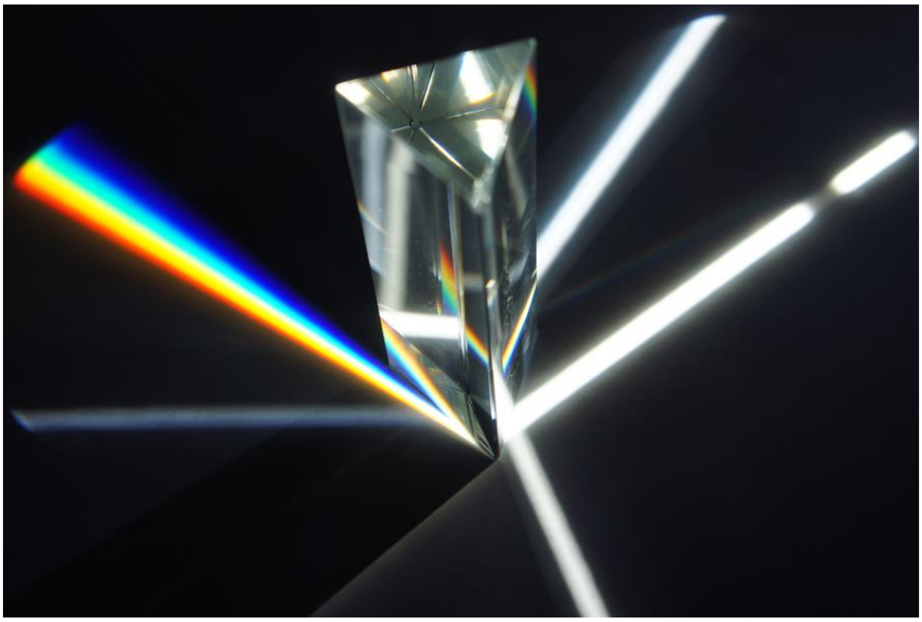

Fig. 4: a prism separating the sunlight into lights with different colors

So, is he the one who discovered that light is a wave? No. While he showed that white light is the mixture of light with different colors, he never claimed that light with different colors has different wavelengths. Actually, he argued that light consists of particles. On the other hand, some other physicists, most notably, the Dutch physicist Huygens argued that light consists of waves. There were heated debates among them. Newton argued that light is composed of particles because if it were a wave, it could bend through bent pipes and go around a corner as waves such as sound can do. If somebody says something over bent pipes, and you press your ear on its other end, you are able to listen to what he says, because sound waves can bend through the bent pipes. However, you will not be able to see him/her. Similarly, if somebody says something on the street and you are behind a corner, you can still hear him/her, even though you cannot see him/her. We now know that Newton argued that light is composed of particles from wrong reasons. Light (more precisely, "visible light" as there are kinds of light that are *not* visible) cannot go around a corner or through bent pipes, not because it is not a wave, but because its wavelength is too short to do so. The wavelength of visible light ranges from 380 nm to 700 nm, which is much shorter than the size of bent pipes or corners. ("nm" is pronounced as "nanometer." "Nano" denotes 10^{-9}). Sound can go around a corner or through bent pipes because its wavelength is comparable to or bigger than the size of pipes and corners. We will have an occasion to talk more about it in "Huygens' principle."

Huygens argued that light was a wave from the correct reasons. He correctly explained the refraction of light (i.e., bending of light when it enters different materials such as from air to glass or water. This is the mechanism behind magnifier and glasses.) and the reason why you see various beautiful colors on thin soap films. We will talk about them in "Huygens' principle" and "Interference from thin films." It is interesting to note that, in this debate, many scientists in England supported Newton, and many scientists in continental Europe supported Huygens.

In the early 19th century, Thomas Young made a breakthrough in the investigation on the light. He conclusively showed that light consists of waves. So, the debate was settled (or seemed to be settled). We will talk about his achievement in "Young's interference experiment."

However, as we will see in the next article, in the early 20th century, Planck and Einstein showed that that light consists of particles is also a right statement. Of course, not for any of the reasons which Newton argued for.

Problem 1. Speed of sound at room temperature is about 340 m/s. The frequency of the musical note A4 is 440 Hz. ("La" sound. You can hear this note here: https://www.youtube.com/watch?v=buimPG01gcs). What is the wavelength of this sound? Check that it is indeed comparable to the size of pipes and corners.

Problem 2. Radio wave is a kind of light that is not visible to human eyes. The speed of light is 299,792,458 m/s. Explain why you can get the radio signal from your favorite radio station 95 MHz, even though this radio station is blocked from your view by mountains and buildings.

Summary

- Light and sound are waves. In the case of light, its wavelength determines the color, and in case of sound, its wavelength determines the pitch.

- Newton discovered that white light is a mixture of all the light with different colors. One can decompose it into its original component using a prism.
- Newton argued that light is particles, while Huygens argued that light is waves. The debate was settled by Young's experiments in the early 19^{th} century. Light is waves.
- The frequency of a wave is defined by $f=1/T$, where T is its period.
- The speed of a wave is given by $v=\lambda f$, where λ is its wavelength.
- In the early 20^{th} century, Planck and Einstein discovered that light is also particles. But, not for any of the reasons Newton argued for.