The Nature of Light

To access a customizable version of this book, as well as other interactive content, visit www.ck12.org

CK-12 Foundation is a non-profit organization with a mission to reduce the cost of textbook materials for the K-12 market both in the U.S. and worldwide. Using an open-content, web-based collaborative model termed the **FlexBook®**, CK-12 intends to pioneer the generation and distribution of high-quality educational content that will serve both as core text as well as provide an adaptive environment for learning, powered through the **FlexBook Platform®**.

Printed: May 4, 2013

flexbook
next generation textbooks

CONCEPT 1

The Nature of Light

Lesson Objectives

The student will:

- perform calculations involving the relationship between the wavelength and frequency of electromagnetic radiation, $v = \lambda f$.
- perform calculations involving the relationship between the energy and the frequency of electromagnetic radiation, $E = hf$.
- state the velocity of electromagnetic radiation in a vacuum.
- name at least three different areas of the electromagnetic spectrum.
- when given two comparative colors or areas in the electromagnetic spectrum, identify which area has the higher wavelength, the higher frequency, and the higher energy.

Vocabulary

- amplitude
- crest
- electromagnetic spectrum
- frequency (f)
- hertz (Hz)
- trough
- velocity (v)
- wavelength (λ)

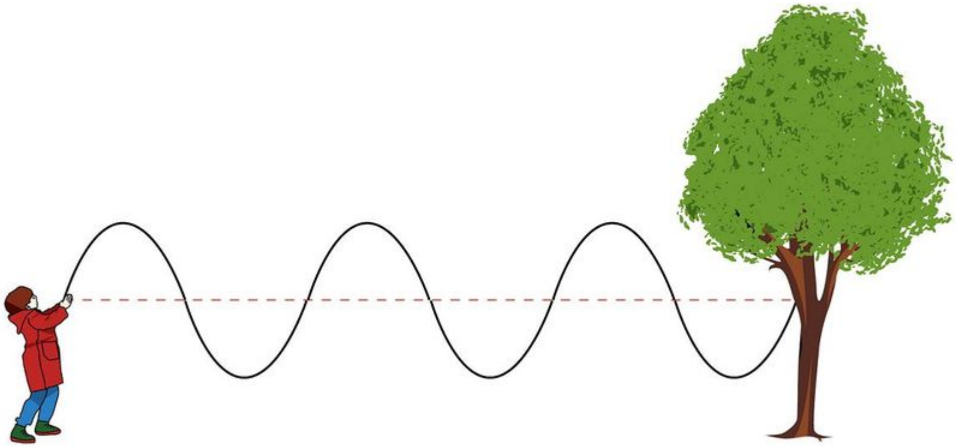
Introduction

In order to understand how Rutherfod's model of the atom evolved to the current atomic model, we need to understand some basic properties of light. During the 1600s, there was a debate about how light travels. Isaac Newton, the English physicist, hypothesized that light consisted of tiny particles and that a beam of light would therefore be a stream of particles. Around the same time, Christian Huygens, a Dutch physicist, suggested that light traveled as a waveform in the same way energy travels in water.

Neither hypothesis became the dominant idea until 200 years later, when the Scottish physicist James Clerk Maxwell proposed a wave model of light in 1864 that gained widespread support. Maxwell's equations related electricity, magnetism, and light so comprehensively that several physicists suggested students should major in other sciences because everything in physics had been discovered. Scientists thought that Maxwell's work permanently settled the "wave versus particle" debate over the nature of light. Fortunately, quite a few students did not take their advice. Sixty years later, German physicist Max Planck would raise the issue again and renew the debate over the nature of light.

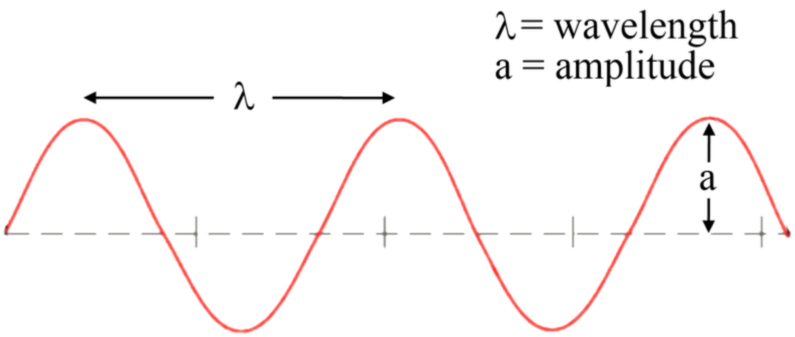
The Wave Form of Energy

The wave model of electromagnetic radiation is somewhat similar to waves in a rope. Suppose we tie one end of a rope to a tree and hold the other end at a distance from the tree so that the rope is fully extended. If we then jerk the end of the rope up and down in a rhythmic way, the rope will go up and down. When the end of the rope we are holding goes up and down, it pulls on the neighboring part of the rope, which will also go up and down. The up and down motion will be passed along to each succeeding part of the rope, and after a short time, the entire rope will contain a wave like the one shown in the image below.



The red line in the diagram shows the undisturbed position of the rope before the wave motion was initiated. The **crest** is the highest point of the wave above the undisturbed position, while the **trough** is the lowest point of a wave below the undisturbed position. It is important for you to recognize that the individual particles of rope *do not move horizontally*. Each point on the rope only moves up and down. If the wave is allowed to dissipate, every point of the rope will be in the exact same position it was in before the wave started. The wave in the rope moves horizontally from the person to the tree, but no parts of rope actually move horizontally. The notion that parts of the rope are moving horizontally is a visual illusion. Like the wave, the energy that is put into the rope by jerking it up and down also moves horizontally from the person to the tree.

If we jerk the rope up and down with a different rhythm, the wave in the rope will change its appearance in terms of crest height, distance between crests, and so forth, but the general shape of the wave will remain the same. We can characterize the wave in the rope with a few measurements. The image below shows an instantaneous snapshot of the rope so that we can indicate some characteristic values.



The distance from one crest to the next crest is called the **wavelength** of the wave. You could also determine the wavelength by measuring the distance from one trough to the next or between any two identical positions on successive waves. The symbol used for wavelength is the Greek letter lambda, λ. The distance from the maximum height of a crest to the undisturbed position is called the **amplitude** of the wave. The **velocity** of a wave is the distance traveled by the wave in one second. We can obtain the velocity of the wave by measuring how far a crest travels horizontally in a unit of time. The SI unit for velocity is meters/second.

Another important characteristic of waves is called frequency. The **frequency** of a wave is the number of cycles that pass a given point per unit of time. If we choose an exact position along the path of the wave and count how many crests pass the position per unit time, we would get a value for frequency. Based on this description, the unit for frequency would be cycles per second or waves per second. In science, however, frequency is often denoted by 1/s or s^{-1}, with "cycles" being implied rather than explicitly written out. This unit is called a **hertz** (abbreviated Hz), but it means cycles per second and is written out in calculations as 1/s or s^{-1}. The symbol used for frequency is the Greek letter nu, ν. Unfortunately, this Greek letter looks a very great deal like the italicized letter v. You must be very careful when reading equations to see whether the symbol is representing velocity (v) or frequency (ν). To avoid this problem, this text will use a lower case letter f as the symbol for frequency.

The velocity, wavelength, and frequency of a wave are all related, as indicated by the formula: $v = \lambda f$. If the wavelength is expressed in meters and the frequency is expressed in 1/second (s^{-1}), then multiplying the wavelength times the frequency will yield meters/second, which is the unit for velocity.

Example:

What is the velocity of a rope wave if its wavelength is 0.50 m and its frequency is 12 s^{-1}?

$$v = \lambda f = (0.50\text{ m}) \cdot (12\text{ s}^{-1}) = 6.0\text{ m/s}$$

Example:

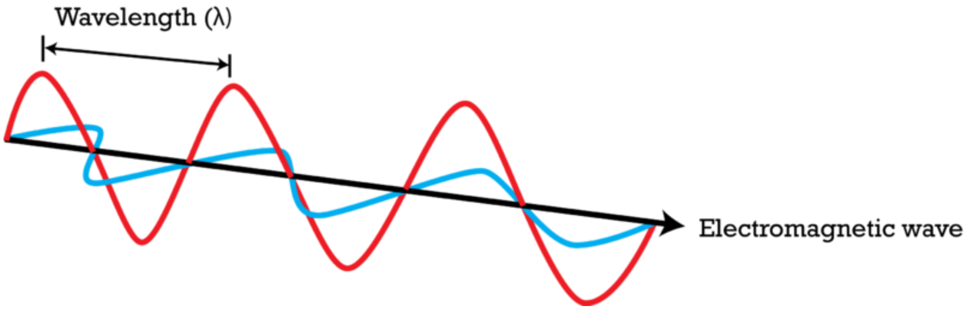
What is the wavelength of a water wave if its velocity is 5.0 m/s and its frequency is 2.0 s^{-1}?

$$\lambda = \frac{v}{f} = \frac{5.0\text{ m/s}}{2.0\text{ s}^{-1}} = 2.5\text{ meters}$$

Electromagnetic Waves

Electromagnetic radiation is a form of energy that consists of electric and magnetic fields traveling at the speed of light. Electromagnetic waves carry this energy from one place to another and are somewhat like waves in a rope. Unlike the wave in a rope, however, electromagnetic waves are not required to travel through a medium. For example, light waves are electromagnetic waves capable of traveling from the sun to Earth through outer space, which is considered a vacuum.

The energy of an electromagnetic wave travels in a straight line along the path of the wave, just like the energy in the rope wave did. The moving light wave has associated with it an oscillating electric field and an oscillating magnetic field. Scientists often represent the electromagnetic wave with the image below. Along the straight-line path of the wave, there exists a positive electric field that will reach a maximum positive charge, slowly collapse to zero charge, and then expand to a maximum negative charge. Along the path of the electromagnetic wave, this changing electric field repeats its oscillating charge over and over again. There is also a changing magnetic field that oscillates from maximum north pole field to maximum south pole field. Do not confuse the oscillating electric and magnetic fields with the way light travels. Light does not travel in this weaving wave pattern. The light travels along the black line that represents the undisturbed position. For an electromagnetic wave, the crests and troughs represent the oscillating fields, not the path of the light.



Although light waves look different from the wave in the rope, we still characterize light waves by their wavelength, frequency, and velocity. We can measure along the path of the wave the distance the wave travels between one crest and the succeeding crest. This will be the wavelength of the electromagnetic radiation. The frequency of electromagnetic waves is still the number of full cycles of waves that pass a point in a unit of time, just like how frequency is defined for rope waves. The velocity for all electromagnetic waves traveling through a vacuum is the same. Although technically the velocity of electromagnetic waves traveling through air is slightly less than the velocity in a vacuum, the two velocities are so close that we will use the same value for the velocity. In a vacuum, every electromagnetic wave has a velocity of 3.00×10^8 m/s, which is symbolized by the lower case c. The relationship, then, for the velocity, wavelength, and frequency of electromagnetic waves is: $c = \lambda f$.

Example:

What is the wavelength of an electromagnetic wave traveling in air whose frequency is $1.00 \times 10^{14}\ \text{s}^{-1}$?

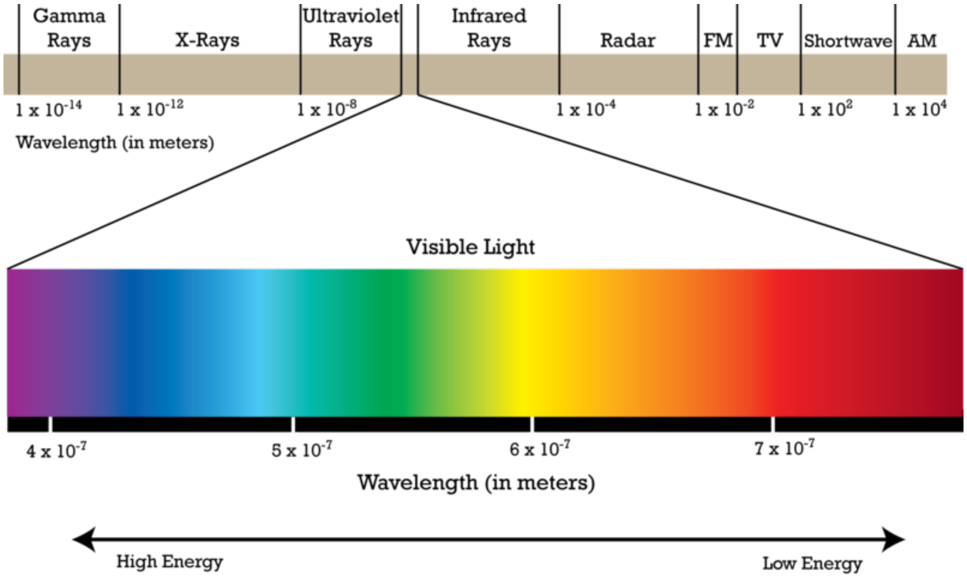
$$\lambda = \frac{c}{f} = \frac{3.00\times10^8\ \text{m/s}}{1.00\times10^{14}\ \text{s}^{-1}} = 3.00 \times 10^{-6}\ \text{m}$$

The Electromagnetic Spectrum

In rope waves and water waves, the amount of energy possessed by the wave is related to the amplitude of the wave; there is more energy in the rope if the end of the rope is jerked higher and lower. In electromagnetic radiation, however, the amount of energy possessed by the wave is only related to the frequency of the wave. In fact, the frequency of an electromagnetic wave can be converted directly to energy (measured in joules) by multiplying the frequency with a conversion factor. The conversion factor is called Planck's constant and is equal to 6.6×10^{-34} joule · seconds. Sometimes, Planck's constant is given in units of joules/hertz, but you can show that the units are the same. The equation for the conversion of frequency to energy is $E = hf$, where E is the energy in joules (symbolized by J), h is Planck's constant in joules·second, and f is the frequency in s^{-1}.

Electromagnetic waves have an extremely wide range of wavelengths, frequencies, and energies. The **electromagnetic spectrum** is the range of all possible frequencies of electromagnetic radiation. The highest energy form of electromagnetic waves is gamma rays and the lowest energy form (that we have named) is radio waves.

In the image below, the electromagnetic waves on the far left have the highest energy. These waves are called gamma rays, and they can cause significant damage to living systems. The next lowest energy form of electromagnetic waves is called X-rays. Most of you are familiar with the penetration abilities of these waves. Although they can be helpful in imaging bones, they can also be quite dangerous to humans. For this reason, humans are advised to try to limit as much as possible the number of medical X-rays they have per year. After X-rays, ultraviolet rays are the next lowest in energy. These rays are a part of sunlight, and rays on the upper end of the ultraviolet range can cause sunburn and eventually skin cancer. The next tiny section in the spectrum is the visible range of light. The band referred to as visible light has been expanded and extended below the full spectrum. These are the frequencies (energies) of the electromagnetic spectrum to which the human eye responds. Lower in the spectrum are infrared rays and radio waves.



The light energies that are in the visible range are electromagnetic waves that cause the human eye to respond when they enter the eye. The eye then sends signals to the brain, and the individual "sees" various colors. The waves in the visible region with the highest energy are interpreted by the brain as violet. As the energy of the waves decreases, the colors change to blue, green, yellow, orange, and red. When the energy of the wave is above or below the visible range, the eye does not respond to them. When the eye receives several different frequencies at the same time, the colors are "blended" by the brain. If all frequencies of visible light enter the eye together, the brain sees white, and if no visible light enters the eye, the brain sees black.

All the objects that you see around you are light absorbers – that is, the chemicals on the surface of the objects absorb certain frequencies and not others. Your eyes will then detect the frequencies that strike them. Therefore, if your friend is wearing a red shirt, it means that the dye in that shirt reflected the red and absorbed all the other frequencies. When the red frequency from the shirt arrives at your eye, your visual system sees red, and you would say the shirt is red. If your only light source was one exact frequency of blue light and you shined it on a shirt that absorbed every frequency of light except for one frequency of red, then the shirt would look black to you because no light would be reflected to your eye.

Lesson Summary

- The wave form of energy is characterized by velocity, wavelength, and frequency.
- The velocity, wavelength, and frequency of a wave are related by the expression: $v = \lambda f$.
- Electromagnetic radiation comes in a wide spectrum that includes low energy radio waves and very high energy gamma rays.
- The frequency and energy of electromagnetic radiation are related by the expression: $E = hf$.

Further Reading / Supplemental Links

This website provides more information about the properties of electromagetic waves and includes an animation showing the relationship between wavelength and color.

- http://micro.magnet.fsu.edu/primer/java/wavebasics/index.html

Review Questions

1. Name at least three different areas in the spectrum of electromagnetic radiation.
2. Which color of visible light has the longer wavelength, red or blue?
3. What is the velocity of all forms of electromagnetic radiation traveling in a vacuum?
4. How can you determine the frequency of a wave when the wavelength is known?
5. If the velocity of a water wave is 9.0 m/s and the wave has a wavelength of 3.0 m, what is the frequency of the wave?
6. If a sound wave has a frequency of 256 Hz and a wavelength of 1.34 m, what is its velocity?
7. What is the relationship between the energy of electromagnetic radiation and the frequency of that radiation?
8. What is the energy, in joules, of a light wave whose frequency is 5.66×10^8 Hz?