# 2.1: The Wave Nature of Light

**Learning Objectives**

- You will know that light can act like either a wave or a particle.
- You will know that all types of light travel at the same speed.
- You will be able to distinguish between wavelength, frequency, and speed. You will be able to perform calculations and understand conceptually the relationship between wavelength, frequency, and speed.

**WHAT DO YOU THINK: COSMIC SPEED LIMIT**

A group of students are working on their astronomy homework.

- **Piper:** Ok, one of the things we have to remember is that all types of light travel at the same speed , the speed of light.
- **Quentin:** Not radio, that travels at the speed of sound.
- **Ricardo:** Yeah, and x-rays have a higher frequency and more energy, so they must travel faster.
- **Sasha:** Radio waves are still light, so I think Piper is right. What I don't understand is how frequency and energy comes into play.



Much of your experience with the world comes from your senses, including your vision. Light enters your eyes, is converted to electrical signals, and is interpreted by your brain, allowing you to explore the world around you.

In the next interactive activity, you will predict what happens when different colors of light compete in a race.

### PHOTON RACE, ROUND ONE

Ladies and gentlemen! Place your bets! Which colors of light do you think travel fastest through the vacuum of empty space?

Now that you have made your predictions, press the “start” button to enjoy the race.

**Play Activity**

After doing this activity, you should see that different colors of light all travel with the same speed in the vacuum of empty space. When you look at the objects around you, it might seem as if you are seeing the light from them infinitely fast because they are so close, but it turns out that light has a speed: $3 \times 10^8$ m/s (in SI units). This is a fundamental constant that scientists call “$c$”—and this speed is the same for light of any color. This is true not just for visible light, but for all forms of light in the electromagnetic spectrum.

You might have heard that light is a wave. In fact, one model of electromagnetic radiation is that of oscillating waves of electric and magnetic fields, i.e., electromagnetic waves. This is a classical model, developed at the end of the 19th century by a British physicist named James Clerk Maxwell (1831 – 1879).

Like water waves, or waves on a string, electromagnetic waves can be characterized by their amplitude, frequency, wavelength, and speed. The wavelength is the distance between adjacent peaks (or adjacent troughs, etc). Frequency is the number of complete waves, or wavelengths, that pass a given point each second. The amplitude of a water wave, or wave on a string, is its height, or how far it rises and drops from its midpoint. The amplitude of an electromagnetic wave is related to the strength of the electric and magnetic fields causing the wave. All light travels at the same speed, but each color has a different wavelength and frequency. Amplitude and wavelength are shown in Figure 2.1.

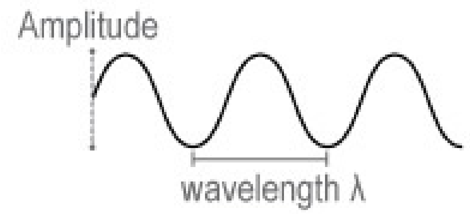


Figure 2.1: Waves are described by several properties, two of which are shown here. The amplitude of the wave is its height, or how far it rises and drops from its midpoint. The wavelength is the distance between adjacent peaks (or adjacent troughs, etc). Waves are also described by the speed at which they travel and by the frequency at which they oscillate. Credit: NASA/SSU/Aurore Simonnet.

Mathematically, the frequency, wavelength, and speed of any wave (not just light) are related by:

$$\text{wavelength} = \frac{\text{speed}}{\text{frequency}}$$

The units of frequency are named hertz in recognition of the contributions to the understanding of waves by Heinrich Hertz (1857 – 1894). Scientists also say “cycles per second” or “inverse seconds” when using the frequency unit hertz, which is written as $s^{-1}$, 1/s, or Hz. Wavelength and frequency are inversely proportional to each other, which means that if the frequency is *bigger* (higher), the wavelength will be *smaller* (shorter) and vice versa.

Given what we have learned about light so far, we can rewrite the equation above so that it applies to light waves:

$$\lambda = \frac{c}{f}$$

where $c$ is the speed of light in m/s, $\lambda$ (Greek letter “lambda”) is the wavelength in meters, and $f$ is the frequency in Hz.

There is another way to think of this equation. If you realize that the frequency is how many waves pass per second, then the reciprocal of the frequency is the time needed for one wave to pass. For example, if ten waves pass each second ($f$ = 10 Hz), then the time needed for one wave to pass is 1/10 Hz = 0.1 seconds. We call the time for one wave to pass the period, $P$, of the wave. So we know that $P = 1/f$. So for any wave, if it has a high frequency, then it has a short period, and vice versa. In other words, if a lot of waves are passing in each second (high frequency), then it doesn't take very much time for a single wave to pass, and the wave has a short period. On the other hand, if it takes a long time for one wave to pass by, then not very many of them will pass each second. We may rewrite the previous equation in terms of the period to get the following very similar equation.

$$\lambda = cP$$

This might not seem like a big improvement. But if you realize that the period is the time for one wave to pass, and that $c$ is the speed it travels, then we know that the product $cP$, the speed times the time, is how far the wave travels over its period. But this is necessarily its wavelength, so this form of the equation makes the relationship between speed, period (or frequency) and wavelength a bit more natural. Unfortunately, scientists generally prefer to think about waves in terms of their frequencies, not their periods. This is unfortunate because, while the two quantities are equivalent in terms of their information about the wave, many beginning students have a hard time understanding what frequency is. But most can understand the notion of period - the time for a single oscillation of the wave - with much less effort. Either way of thinking about this equation is fine as long as you remember that the period is the reciprocal of the frequency.

While the wave model of light precedes the idea of electromagnetic waves by several centuries, Maxwell was the first to realize that the separate equations of classical electricity and classical magnetism could be combined into a single electromagnetic theory that predicted the existence of oscillating electromagnetic fields. With his electromagnetic theory, Maxwell was able to unify the (at that time) separate ideas of radio waves and visible light into a single theoretical framework. The equations also predicted the existence of higher-frequency waves, such as x-rays and gamma-rays. All of these were thereafter understood to be oscillating electromagnetic fields, with radio waves having long wavelengths and low frequencies, and gamma-rays having the opposite extreme of short wavelengths and high frequencies.

Knowing about the wave nature of light helps us interpret the different types of light that astronomical objects emit. In turn, this allows us to employ those waves to learn more about the processes that affect the formation and evolution of stars, galaxies, and the Universe itself.

The next activity, which uses the interactive Wave Generator tool, will give you some practice working with the ideas of wavelength, frequency, and speed. These are all important properties of waves.

WAVE GENERATOR

A wave generator is a laboratory device that creates wave signals whose properties can be changed by the user. In this activity, you will use a virtual wave generator, where the x-axis shows the wave's wavelength in meters and the y-axis shows the wave's amplitude. The amplitude of a wave essentially describes its intensity, or strength. Wavelength is the distance between two adjacent peaks of a wave. Frequency describes how many wave patterns or cycles pass by a certain point in 1 second.

You can make changes to the basic properties of the wave that is being generated in the following ways:

- Stop the wave generator to measure the wave at any time. Hover your cursor over the graph and you will see an x-y coordinate display of cursor position on the graph. Notice that the origin of the graph is on the far left, in the middle of the y-axis.
- Below the "stop" button, there are the wavelength and amplitude sliders. Use these sliders to increase or decrease the wave's properties in real time.
- There is also a stopwatch that counts time in seconds. You can start and stop the stopwatch, and also reset it to zero when you need to make a new measurement.

Use the *Wave Generator* to conduct the following measurements, and answer the following questions. All the waves generated have the same speed. Only the wavelength and amplitude can be changed with the sliders, though this can also change the frequency of the wave in accordance with the wavelength-frequency-speed relation above.

## Play Activity

**A. Measuring the wavelength of a wave**

**B. Measuring frequency**

To determine the frequency, you will need to count the waves as they pass by a marker in a certain amount of time.

*Worked Example (for a different wavelength):*

Suppose 3 waves pass by the vertical slider bar (orange vertical line) on the wave generator in 3 seconds. What's the frequency?

- Given: Time = 3 seconds, number of waves = 3
- Find: Frequency in cycles per second
- Concept(s): f = number of waves/number of seconds

- Solution: f = 3 waves/3 seconds = 1 cycle per second or 1 Hz

*Questions:*

1. Now use the wavelength of 150 m from the previous section and the stopwatch to determine the frequency. You will need to count the waves as they pass by the orange vertical bar. You can move the bar along the x-axis to a position that is easy for you to watch.

- Start the stopwatch when the peak (or trough) of a wave passes the arrow.
- Let it run until at least 3 waves have passed by the arrow.
- Stop the stopwatch and read out the results for time passed.
- You may want to repeat this activity a few times to make sure you are reading the graph and the stopwatch accurately.

Show your work here:

**C. Measuring wavelength, frequency, and speed.**

We can use the relationship between speed, wavelength and frequency to calculate the speed of a wave.

*Worked Example:*

What is the speed of a wave with wavelength 100 m and frequency 1 Hz?

- Given: Wavelength is 100 m, frequency is 1 Hz
- Find: Speed of the wave in m/s
- Concept(s): speed = (wavelength)x(frequency)
- Solution: speed = 100 m × 1 Hz = 100 m $s^{-1}$ = 100 m/s

*Questions:*

After completing the previous activity, you should have a good idea of what is meant by the frequency and wavelength of a wave. The relation between frequency and wavelength allows us to describe electromagnetic waves (in other words, light) using either frequency or wavelength without introducing any confusion. Scientists are comfortable speaking about light in terms of either frequency or wavelength. They tend to use whichever is most convenient at the time.