At-Home Activity: Light

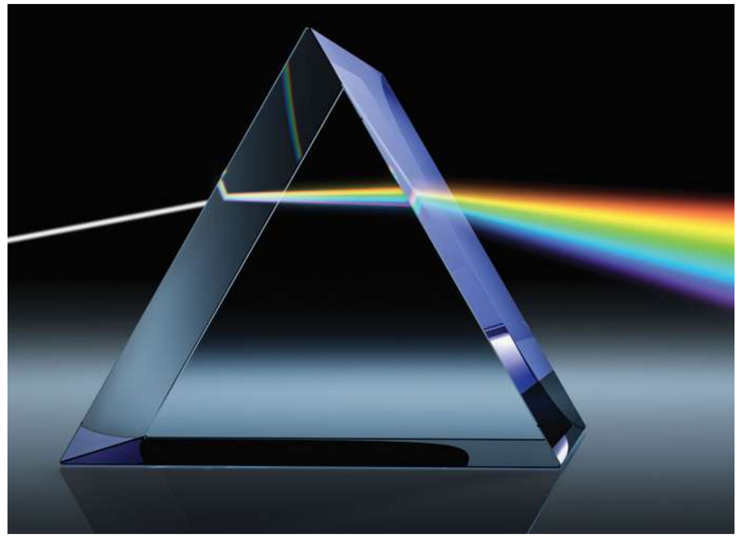


Image Credit: www.britannica.com/science/refraction

One of the major themes of this course is to address the question: “How do we know what we know about the universe?” As a species, we’ve hardly ventured beyond our own planet. Traveling to far away stars and galaxies is impossible with current technology. So if we can’t visit those things, how can we learn about them?

In a word, the answer is: *light*. Nearly everything we know about objects in the Universe comes to us via the light that reaches us from those objects. Astronomers are like Sherlock Holmes: they can deduce a great deal from just a few small clues. From this point in the course and on, we will unravel this astronomical detective work as we take a look at how information is encoded in light.

Part 1: Models of Light

What exactly *is* light? It is the fastest thing in the Universe. It carries energy. It has zero mass, and yet it still carries momentum and spin. It must always be traveling at the speed of light (it can never slow down or stop). It’s strange stuff!

It was while contemplating the mysterious nature of light that Einstein went down the rabbit hole that led him to relativity and, as we’ll see in a moment, another pivotal discovery.

Light: Is it made of waves or particles?

In the 17th century, **Isaac Newton** proposed that light was composed of little particles. Newton’s contemporary, **Christian Huygens**, disagreed and suggested that light travels in the form of waves. So which is it? By the late 19th and early 20th century, scientists had a large amount of evidence supporting both ideas!

Today we accept that there are two models for light: it can behave *either* like a particle or a wave. Both models are very effective, and the best one to use depends on the given situation. This strange conclusion from quantum physics is called **wave-particle duality**.

Wave Model of Light

What does “wave behavior” mean, anyway? One characteristic of waves is that they exhibit the behavior of **interference**: waves can add together or cancel each other out. If you’re familiar with or have experienced an acoustical “dead spot” in an auditorium, that is an example of interference: since sound is a wave, sound waves can sometimes cancel each other out.

Waves exhibit interference; they can add or cancel

In 1801, Thomas Young experimentally demonstrated that light can behave like waves. Young showed that light exhibits interference in exactly the same way that water waves do (see image). Light waves can add together or cancel each other out. This made an extremely strong case for light being a wave.

In the 1860’s, Scottish physicist James Clerk Maxwell showed mathematically that light waves are a consequence of electricity and magnetism and that they propagate along electric and magnetic fields like waves on a string. Therefore, we now call light an **electromagnetic wave**.

Particle Model of Light

In this model, light is made of a stream of massless particles called **photons**. With this model one can picture, for instance, a flashlight as a rapid-fire “photon gun” spraying billions upon billions of photons.

In 1905, Einstein showed that light can behave like particles by observing something called the **photoelectric effect**. In the photoelectric effect, an incoming photon hits a piece of metal and liberates an electron from the metal.

> *Little known fact*: Einstein won his Nobel Prize in Physics for his discovery of the photoelectric effect and NOT for relativity.

> *Another cool Einstein fact*: Einstein discovered the photoelectric effect and relativity, including his famous formula $E = mc^2$, in the same year. 1905 is now called his *annus mirabilis* (“miracle year”).

Aside on Quantum Physics: Photons (particles of light) are not the only particles that exhibit wave-particle duality. All subatomic particles do! This includes electrons, protons, quarks, etc. The fact that an electron can behave like a wave is the principle behind how an **electron microscope** uses electrons to create images of microscopic objects.

Ray Model of Light

There is yet another model for light. In this model, light is treated as a "ray". In other words, light travels along a straight line like an arrow. It is actually a simplification of the wave model, rather than a new model in its own right. Unlike the previous two models, the ray model focuses on macroscopic behavior and therefore the ray model is sufficient and convenient for understanding things like optics and telescopes.

SQ1: Has science failed if it hasn't been able to pin down the "true" nature of light? Think back to the "Scientific Models" pre-Lab. What is the goal of science? With light, has it accomplished that goal?

Part 2: The Electromagnetic Spectrum

In this course we will mostly be using the wave model of light. Therefore, when we say *light*, we are typically referring to **electromagnetic waves** (or synonymously, **electromagnetic radiation**).

Visible light (i.e., the light that we see with our eyes) is just one type of electromagnetic radiation. You've surely heard of other types of electromagnetic radiation.

STEP 1: Make a list below of all of the phrases and terms that you can think of that utilize the word *wave* or *ray*. Try to get at least 10. Go ahead, be creative.

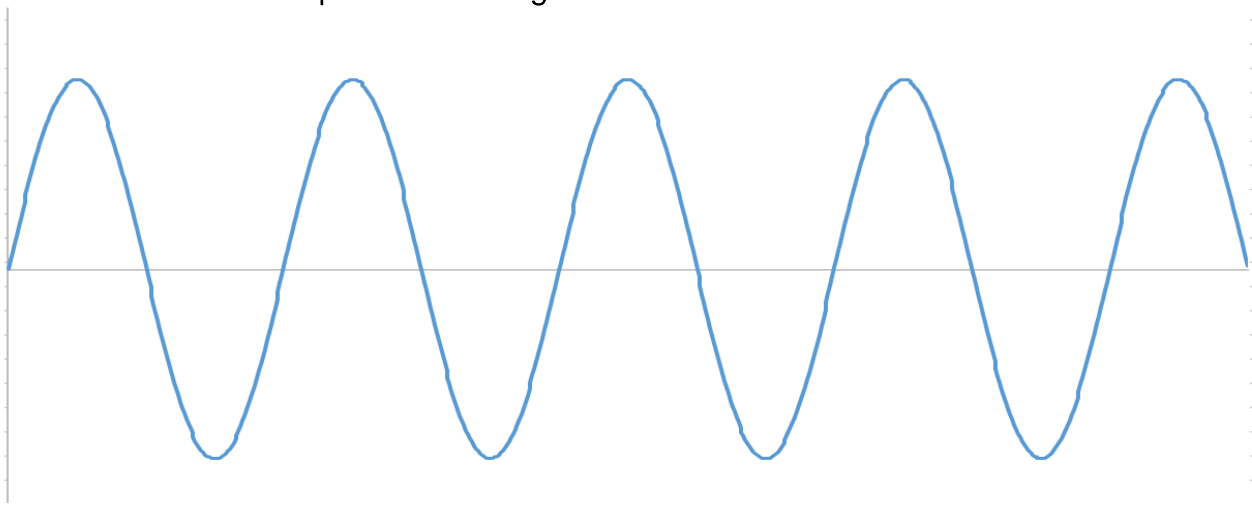
Now, consult this figure https://tinyurl.com/8jzr563d to see a list of the types of electromagnetic waves. Circle all of the electromagnetic waves in your list.

All types of **electromagnetic radiation** (including all of the things you've circled in your list above) are made of electromagnetic waves (or photons). Therefore, *all* of them travel at the *speed of light*. The only thing that differentiates the types of electromagnetic radiation is their frequency (and equivalently, as we'll see soon, their wavelength).

Wavelength and Frequency

First, let's do a quick refresher on what *wavelength* and *frequency* mean.

Electromagnetic radiation is a **wave**. Below we have drawn a wave. Notice that it consists of a series of peaks and troughs.



STEP 2: Using a pen or highlighter, highlight *one whole cycle* of the wave. Suggestion: start highlighting at a point where the wave crosses the x-axis (crossing from below to above) and continue highlighting until you've reached a point where the wave is again crossing the x-axis from below to above.

How to test your answer: If you were to photocopy your highlighted cycle over and over again, would you exactly recreate the wave pattern shown? You should answer yes. If not, check your answer to the previous question.

The **wavelength** is the distance from one peak to the next peak.

STEP 3: Draw a horizontal line connecting two adjacent peaks on the wave above to indicate one wavelength, and label it "wavelength".

Which peaks did you choose to connect with the line? If you chose peaks #1 and #2, would it have mattered if you'd chosen peaks #2 and #3? That is, would the wavelength be any different for different pairs of adjacent peaks?

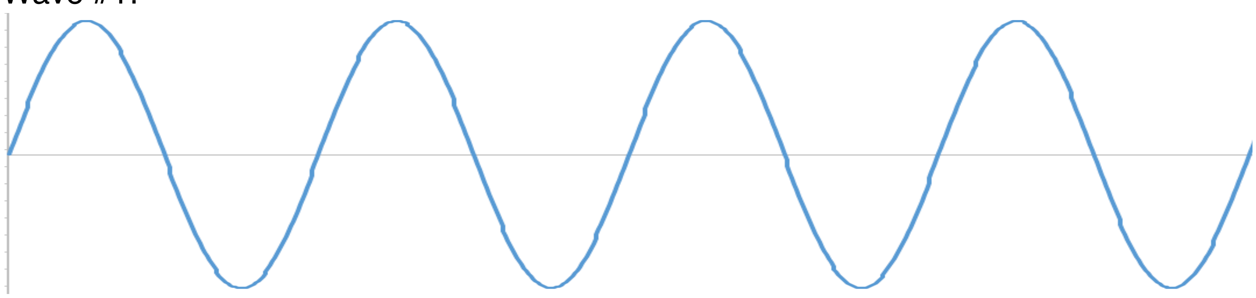
Consider the distance from one trough to the next trough. Draw a horizontal line on the wave above that connects a trough and an adjacent trough. How does the length of your new line compare to the length of the one you drew from peak to peak? You may use a ruler to compare them if you like.

STEP 4: As you just saw in the previous Step, a wave consists of a series of repeating patterns. The length of the pattern that repeats is called the wavelength.

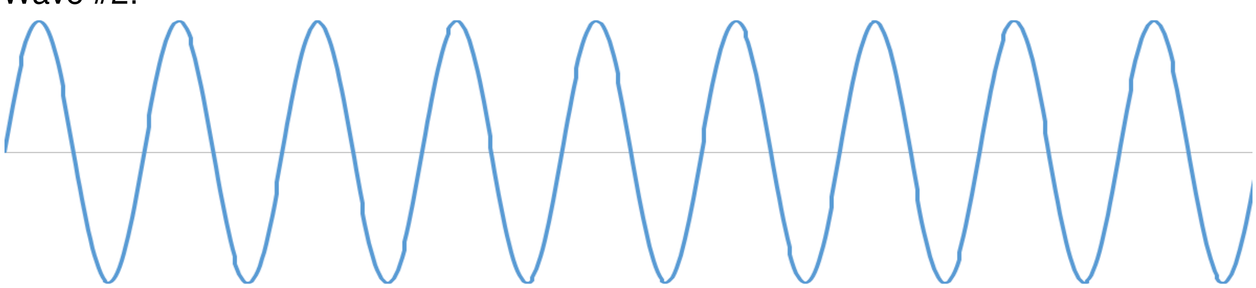
The **frequency** is the *number of times* that a pattern repeats in a given interval of time.

Consider the two waves below. Suppose each of these waves are depicted over a 1 second interval.

Wave #1:



Wave #2:

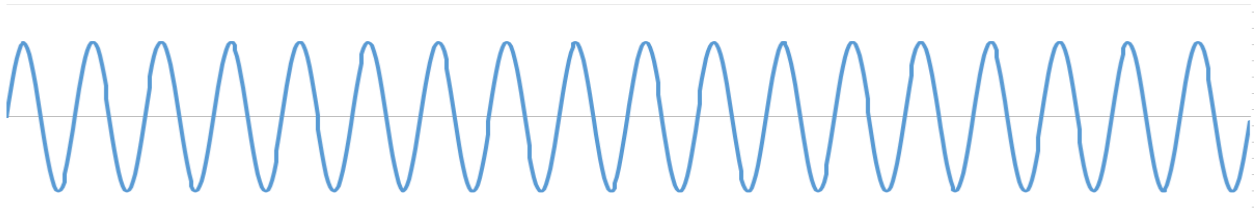


What is the frequency of the first wave (in *number of cycles per second*, which is called **Hertz** or just **Hz**)?

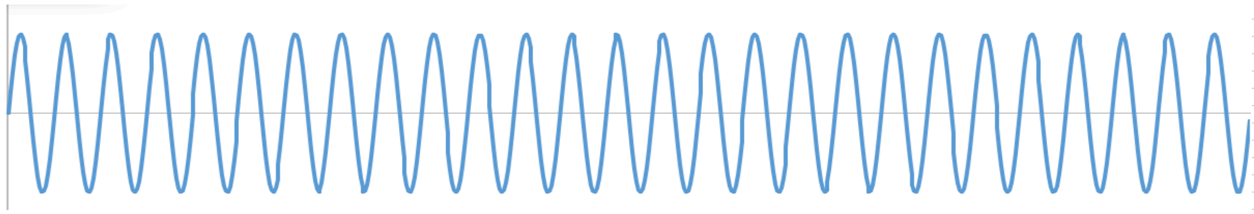
What is the frequency of the second wave (also in Hz)?

STEP 5: Consider the two waves drawn below, A and B. Both are depicted over a 1 second interval.

Wave A:



Wave B:



Which one (A or B) has the greater wavelength? How can you tell?

Which one (A or B) has the greater frequency? How can you tell?

SQ2:

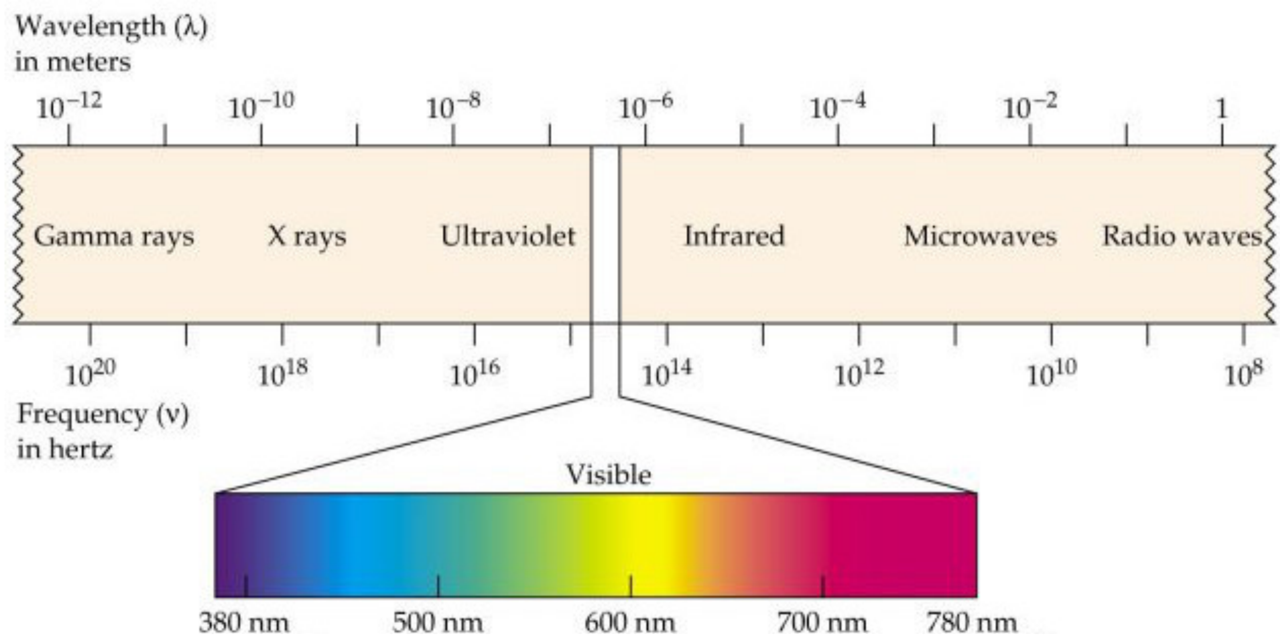
a) As the *wavelength* of a wave *increases*, what happens to the wave's *frequency*? Use waves A and B above for guidance.

b) As the wavelength of a wave *decreases*, what happens to the wave's frequency?

c) Based on your answers to (a) and (b), what kind of relationship (*direct* or *inverse*) exists between frequency and wavelength?

From here on, we will employ these widely-used adjectives for wavelength and frequency: A large wavelength is said to be *long* and a small wavelength is said to be *short*. A large frequency is said to be *high* and a small frequency is said to be *low*.

STEP 6: Consider the diagram below. This shows the **electromagnetic spectrum**, which is a *list* of *all* types of electromagnetic radiation, *sorted* by their wavelength and frequency.



Looking from left to right, is the spectrum sorted in order of increasing wavelength or decreasing wavelength?

Looking from left to right, is this spectrum sorted in order of increasing frequency or decreasing frequency?

Which type of radiation has the shortest wavelength?

Which has the longest wavelength?

Which type of radiation has the lowest frequency?

Which has the highest frequency?

What is the *shortest wavelength* (approximately, in nanometers) that the human eye can see?

What is the *longest wavelength* (approximately, in nanometers) that the human eye can see?

Speed of Light

The **speed of light** is about 300,000,000 meters per second.
$c = 3 \times 10^8$ m/s
That is equal to about 186,000 miles *per second*.

SQ3:

a) What is the speed of radio waves? You may answer in words, or with a number, or with a single letter. *Hint:* Re-read the boxed text near the beginning of this Part (top of page 4).

b) What is the speed of x-rays?

c) The circumference of the Earth is about 25,000 miles. About how many times could light circle the Earth in a single second?

Light Energy

STEP 7: The energy of a wave is *directly* proportional to the wave's *frequency*. Which type of electromagnetic radiation has the most energy?

Most energetic type of electromagnetic radiation:

Which type has the least energy?

Least energetic type of electromagnetic radiation:

List all of the types of electromagnetic radiation that have *more energy than visible light*.

All of the types of electromagnetic radiation you listed above are hazardous to human health because of their high energy. For some of these, you may already be aware of its hazardous nature from your experiences. Give one or two examples.

SQ4:

a) Bluetooth technology uses 2.45 GHz electromagnetic waves to communicate between devices. What part of the electromagnetic spectrum is this? Note: 1 GHz = 10^9 Hz

b) Are Bluetooth signals likely to cause cancer in humans? How do you know?

<u>Colors of Visible Light</u>

All colors that we see can be made by a combination of the colors that are shown in the visible spectrum above. What colors appear in the visible spectrum? Don't worry about shades, just write down basic color names like blue, red, etc.

Notice that *white* and *black* do not appear in your list above (i.e., they are not colors of the rainbow). Where do white and black fit in?

Black is simply the absence of light (i.e., the absence of all colors). **White** light is the opposite: it is a combination of all colors in roughly equal amounts. Notice this is very much *unlike* mixing paints! That's because we are talking about light here, not pigment.

> <u>Aside</u>: You have probably heard of "white noise". Why is it called *white* noise? It's because it consists of many audible sound wave frequencies mixed together in roughly equal amounts. This is the same usage of the word *white* as we see in light: white light consists of many electromagnetic wave frequencies mixed together in roughly equal amounts.

Traditional incandescent light bulbs, as well as the Sun and many stars, emit *white light*. Much of the light we experience in our daily lives is white light.

If you pass white light through a prism or a diffraction grating, it will be split into its constituent colors. You've seen this effect when light reflects off of a CD or DVD.

> The **different colors** that we see are the way in which our visual system interprets different wavelengths of radiation.
>
> Each **color of the rainbow** is a form of electromagnetic radiation, and like other forms of radiation, the only thing that differentiates the colors of visible light is their wavelength (or frequency).

The order of the colors that we see in a rainbow is always the same. An often-used mnemonic for this is "ROYGBV", pronounced "Roy G. Biv" as if it were someone's name. What do the letters ROYGBV each stand for?

SQ5:

a) In what order is ROYGBV (in terms of frequency, wavelength, etc)?

b) Which color of visible light has the least energy? Which color has the most energy?

Least energy: Most energy:

c) In terms of the electromagnetic wave model for light, what is the only difference between red and blue light?

Infrared and **ultraviolet** radiation are *just beyond* what our vision is capable of seeing. Notice that infrared is just before red on the electromagnetic spectrum, and ultraviolet is just beyond violet. This is where *infra**red*** and *ultra**violet*** get their names. Some animals, like reptiles, have evolved to see not only visible light but ultraviolet or infrared radiation as well.