Chapter 12

12 Nature of Light and Reflection 3.1.1, 3.1.2

In the movie *Star Wars* inter-galactic star ships blast each other with laser cannons. The laser beams streak across the screen. This is dramatic, but not realistic. For us to see the light, some of the light must get to our eyes. The light must either travel directly to our eyes from the source, or it must bounce off of something. We can make a laser beam visible by providing dust for the light to bounce off of so it travels to our eyes. But unless that galaxy far far away is really dusty, Hollywood doesn't understand light waves very well. Let's start our study of geometric optics with a few comments on what light is. Then let's study reflection, the bouncing of light off of an object (like dust, or a mirror). Question 223.13.4

Fundamental Concepts

- Light is a wave in the electromagnetic field
- Light travels fast, with a speed of $c = 3 \times 10^8\,\mathrm{m/s}$
- Law of Reflection

12.1 What is Light?

Before the 19th century (1800's) light was assumed to be a stream of particles. Newton was one of the chief proponents of this theory. The theory was able to explain reflection of light from mirrors and other objects and therefore explain vision. In 1678 Huygens showed that wave theory could also explain reflection and vision.

In 1801 Thomas Young demonstrated that light had attributes that were best explained by wave theory. We will study Young's experiment later. The crux of his experiment was to show that light displayed constructive and destructive interference–clearly a wave phenomena! The theory of the nature of light took a dramatic shift

In 1805 Joseph Smith was born in Sharon, Vermont.

In September of 1832 Joseph Smith received a revelation that said in part :

> For the word of the Lord is truth, and whatsoever is truth is light, and whatsoever is light is Spirit, even the Spirit of Jesus Christ. And the Spirit giveth light to every man that cometh into the world; and the Spirit enlighteneth every man through the world, that hearkeneth to the voice of the Spirit. (D&C 84:45-46)

In December of 1832 Joseph Smith received another revelation that says in part:

> This Comforter is the promise which I give unto you of eternal life, even the glory of the celestial kingdom; which glory is that of the church of the Firstborn, even of God, the holiest of all, through Jesus Christ his Son—He that ascended up on high, as also he descended below all things, in that he comprehended all things, that he might be in all and through all things, the light of truth; which truth shineth. This is the light of Christ. As also he is in the sun, and the light of the sun, and the power thereof by which it was made. As also he is in the moon, and is the light of the moon, and the power thereof by which it was made; as also the light of the stars, and the power thereof by which they were made; and the earth also, and the power thereof, even the earth upon which you stand. And the light which shineth, which giveth you light, is through him who enlighteneth your eyes, which is the same light that quickeneth your understandings; which light proceedeth forth from the presence of God to fill the immensity of space—the light which is in all things, which giveth life to all things, which is the law by which all things are governed, even the power of God who sitteth upon his throne, who is in the bosom of eternity, who is in the midst of all things. (D&C 88:5-12)

Light, even real, physical light, seems to be of interest to members of the Restored Church.

In 1847 the saints entered the Salt Lake Valley.

In 1873 Maxwell published his findings that light is an electromagnetic wave (something we will try to show before this course is over!).

Planck's work in quantization theory (1900) was used by Einstein In 1905 to give an explantation of the photoelectric effect that again made light look like a particle.

Current theory allows light to exhibit the characteristics of a wave in some situations and like a particle in others. We will study both before the end of our optics unit.

The results of Einstein's work give us the concept of a *photon* or a quantized unit of radiant energy. Each "piece of light" or photon has energy

$$E = hf \tag{12.1}$$

where f is the frequency of the light and h is a constant

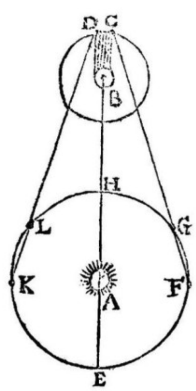
$$h = 6.63 \times 10^{-34}\,\mathrm{J\,s} \tag{12.2}$$

The nature of light is fascinating and useful both in physical and religious areas of thought.

12.2 Measurements of the Speed of Light

One of the great foundations of modern physical theory is that the speed of light is constant in a vacuum. Galileo first tried to measure the speed of light. He used two towers in town and placed a lantern and an assistant on each tower. The lanterns had shades. The plan was for one assistant to remove his shade, and then for the assistant on the other tower to remove his shade as soon as he saw the light from the first lantern. Back at the first tower, the first assistant would use a clock to determine the time difference between when the first lantern was un-shaded, and when they saw the light from the second tower. The light would have traveled twice the inter-tower distance. Dividing that distance by the time would give the speed of light. You can probably guess that this did not work. Light travels very quickly. The clocks of Galileo's day could not measure such a small time difference. Ole Rømer was the first to succeed in measuring the speed of light.

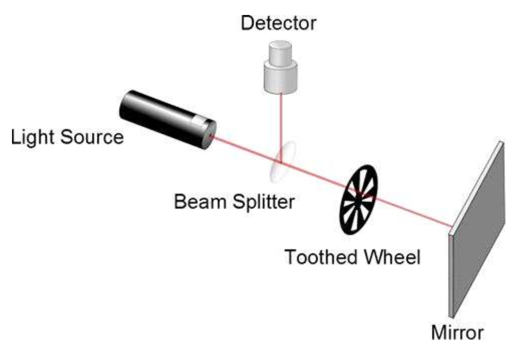
12.2.1 Rømer's Measurement of the speed of light



A diagram illustrating Rømer's determination of the speed of light. Point A is the Sun, piont B is Jupiter. Point C is the immersion of Io into Jupiter's shadow at the start of an eclipse

Rømer performed his measurement in 1675, 269 years before digital devices existed!. He used the period of revolution of Io, a moon of Jupiter, as Jupiter revolved around the sun. He first measured the period of Io's rotation about Jupiter, then he predicted an eclipse of Io three months later. But he found his calculation was off by 600 s. After careful thought, he realized that the Earth had moved in its orbit, and that the light had to travel the extra distance due to the Earth's new position. Given Rømer's best estimate for the orbital radius of the earth and his time difference, Rømer arrived at a estimate of $c = 2.3 \times 10^8 \frac{\text{m}}{\text{s}}$. Amazing for 1675!

12.2.2 Fizeau's Measurement of the speed of light



Hippolyte Fizeau measured the speed of light in 1849 using the apparatus indicated in the figure above. He used a toothed wheel and a mirror and a beam of light. The light passed through the open space in the wheel's teeth as the wheel rotated. Then was reflected by the mirror. The speed would be

$$v = \frac{\Delta x}{\Delta t}$$

We just need Δx and Δt.

It is easy to see that

$$\Delta x = 2d$$

because the light travels twice the distance to the mirror (d) and back. If the wheel turned just at the right angular speed, then the reflected light would hit the next tooth and be blocked. Think of angular speed

$$\omega = \frac{\Delta \theta}{\Delta t}$$

so the time difference would be

$$\Delta t = \frac{\Delta \theta}{\omega}$$

we find $\Delta\theta$ by taking 2π and dividing by the number of teeth on the wheel.

$$\Delta\theta = \frac{2\pi}{N_{teeth}}$$

Then the speed of light must be

$$\begin{aligned} c &= v = \frac{2d}{\frac{\Delta\theta}{\omega}} \\ &= \frac{2d\omega}{\Delta\theta} \\ &= \frac{2d\omega N_{teeth}}{2\pi} \\ &= \frac{d\omega N_{teeth}}{\pi} \end{aligned}$$

then if we have 720 teeth and ω is measured to be $d = 7500\,\mathrm{m}$

$$\begin{aligned} c &= \frac{(7500\,\mathrm{m})\,(172.79\,\mathrm{Hz})\,(720)}{\pi} \\ &= 2.97 \times 10^8\,\frac{\mathrm{m}}{\mathrm{s}} \end{aligned}$$

which is Fizeau's number and it is pretty good!

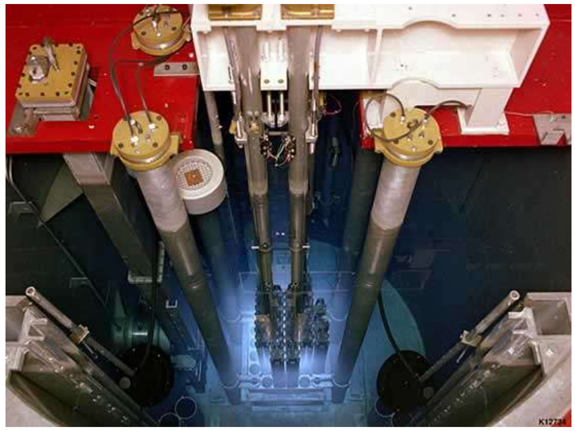
Modern measurements are performed in very much the same way that Fizeau did his calculation. The current value is

$$c = 2.9979 \times 10^8\,\frac{\mathrm{m}}{\mathrm{s}} \tag{12.3}$$

12.2.3 Faster than light

The speed of light in a vacuum is constant, but in matter the speed of light changes.

We will study this in detail when we look at refraction. But for now, a dramatic example is Cherenkov radiation. It is an eerie blue glow around the core of nuclear reactors. It occurs when electrons are accelerated past the speed of light in the water surrounding the core. The electrons emit light and the light waves form a Doppler cone or a light-sonic boom! The result is the blue glow.



Cherenkov radiation (United States Department of Energy, image in the public domain)

This does bring up a problem in terminology. What does the word "medium" mean? We have used it to mean the substance through which a wave travels. This substance must have the property of transferring energy between it's parts, like the coils of a spring can transfer energy to each other, or like air molecules can transfer energy by collision. For light the wave medium is the electromagnetic field. This field can store and transfer energy– but we won't study it until Principles of Physics III (PH220). But many books on physics call materials like glass a "medium" through which light travels. The water in our last example is a "medium" in this sense. Are glass and water wave mediums for light? The answer is an emphatic NO! Light does not need any matter to form it's wave. The wave medium is the electromagnetic field. So we will have to keep this in mind as we allow light to travel through matter. I will try to say that the light enters a new "material" to describe something like light entering a piece of glass. But some books may call the matter a "medium." You must remember that by this they don't mean the wave medium.

Light can't be a wave in some type of matter. We know this because light travels through empty space. But in Principles of Physics III we will find that space isn't exactly empty. It has an electromagnetic field in it. And it turns out that light seems to be a wave in this electromagnetic field. It will take us a while to fully understand this concept–it is done in PH220–but don't worry. Physicists knew that light was a wave for almost 80 years before the electric field was shown to be the medium. We can do a lot just knowing light behaves like a wave.

This makes the light we see just one small part of a whole class of waves that are possible in this electromagnetic field medium. Radio waves, and microwaves, and x-rays are all just different types of electromagnetic waves. The next figure show where all of these electromagnetic waves fit ordered by wavelength (and frequency).

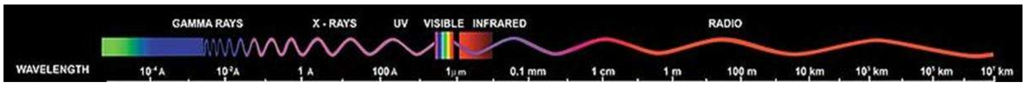


Image Courtesy NASA

There is something very unique about this electromagnetic field medium. The waves in this medium travel at a constant speed no matter what frame of reference we are in. This fact lead to the formation of the Special Theory of Relativity and the famous equation

$$E = mc^2$$

where c is this speed of light

$$c = 299792458 \frac{\mathrm{m}}{\mathrm{s}}$$

Light does slow down when it enters a material, like glass, or even air. This is not really because it moves slower. what happens is that light is absorbed by the electrons in the atoms of the material substance. The electron temporarily takes up all the energy from a bit of the light wave. But only temporarily. It eventually has to give up the energy and a light wave is reformed coming from the atoms. There is really a superposition of what is left of the original light wave, and the new light wave generated by the atoms. And the combined wave moves slower. Think of our last lecture on non-sinusoidal waves. The combined wave is made of two sinusoidal waves both traveling at the speed of light. But the combined wave will appear to travel at a slower speed. How much slower depends on how long the electrons in the atoms can hang on to the light and the geometry of the situation. Each substance is different.

We can devise a way to express how much slower light will appear to go in a substance using the ratio

$$\frac{c}{v}$$

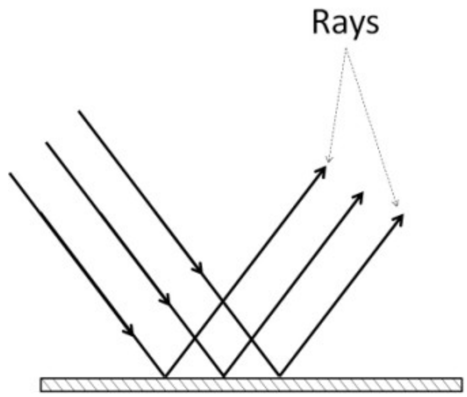
the ratio of the speed of light, c, to the average speed in the substance, v. This ratio is so useful that we give it a name, the *index of refraction*.

$$n = \frac{c}{v}$$

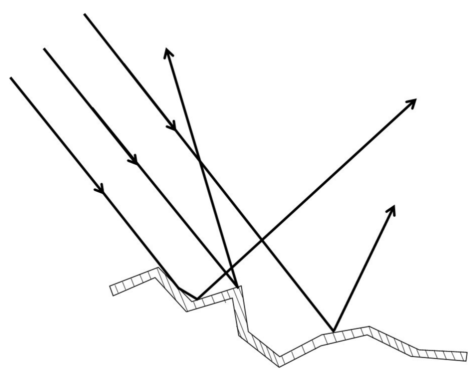
Let's look at some a simple interaction of light with a material, but let's not look at the wave and atomic re-emition level. Let's treat our combined wave as just one resultant wave that travels in a specific direction. We can call this wave a *ray* (as in a ray of light!).

12.3 Reflection

Using the ray approximation we wish to find what happens when a bundle of rays reaches a boundary between materials. If the material boundary is very smooth, then the rays are reflected (bounce off) in a uniform way. This is called *specular* reflection



If the surface is not smooth, then something different happens. The rays are reflected, but they are reflected randomly



This is called *diffuse* reflection

This difference can be seen in real life. In the next figure, the surface on the left is a specular reflector and you can see the reflected light beam. But the surface on the right photo is diffuse, no reflected beam is seen.

We said the surface must be smooth for there to be specular reflection. What does smooth mean? Generally the size of the rough spots must be much smaller than a wavelength to be considered smooth. So suppose we have a red laser. How small do the surface variations have to be for the surface to be considered smooth? The wavelength of a $HeNe$ laser is

$$\lambda_{HeNe} = 633\,\mathrm{nm}$$

This is very small. Modern optics for remote sensing are often manufactured to 1/10 of a wavelength, which would be 63 nm. Mirrors are smooth for visible light.

How about a microwave beam of light like your cell phone uses?

$$\begin{aligned} c &= \lambda f \\ \lambda &= \frac{c}{f} = \frac{3\times 10^8\,\frac{\mathrm{m}}{\mathrm{s}}}{1\,\mathrm{GHz}} \\ &= 0.3\,\mathrm{m} \end{aligned}$$

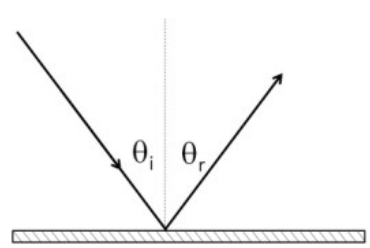
Rough brick walls are smooth for cell phone light!

We can see that we must be careful in our definition of "smooth."

12.4 Law of reflection

Experience shows that if we do have a smooth surface, that light bounces much like a ball. This is why Newton though light was a particle. Suppose we take a flat surface and we shine a light on it. We have a ray that approaches at an angle θ_i measured from the normal. Then the reflected ray will leave the surface with an angle θ_r measured from the normal such that

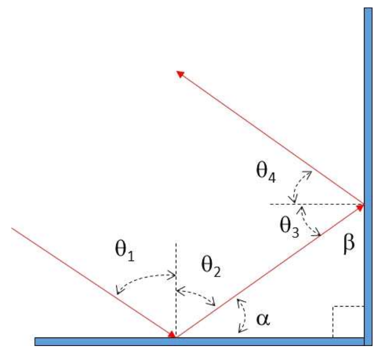
$$\theta_r = \theta_i$$



This is called the *law of reflection*. We will look at how superposition makes this happen later. But from experiment we can see that this law of reflection works.

12.4.1 Retroreflection

Let's take and example



Let's take our system to be two mirrors set at a right angle. We have a beam of light incident at angle θ_1. By the law of reflection, it must leave the mirror at $\theta_2 = \theta_1$. We can see that α must be $90^\circ - \theta_2$ and it is clear that $\theta_3 = \alpha$. By the law of reflection, $\theta_3 = \theta_4$. Then, since

$$90^\circ = \theta_2 + \alpha$$

But now look at the triangle in the corner (that has angles α and β). It's interior angles have to sum to 180, and one of the angles is 90° right in the corner. So

$$180^\circ = 90^\circ + \alpha + \beta$$

Then

$$90^\circ = \alpha + \beta$$

so we can see that β has to be equal to θ_2

$$\beta = \theta_2 = \theta_1$$

and

$$90^\circ = \theta_1 + \theta_4$$

$$\begin{aligned} 90^\circ &= \beta + \theta_3 \\ &= \theta_1 + \theta_3 \end{aligned}$$

and of course by the law of reflection $\theta_3 - \theta_4$then the total angular change is

$$\theta_1 + \theta_2 + \theta_3 + \theta_4$$

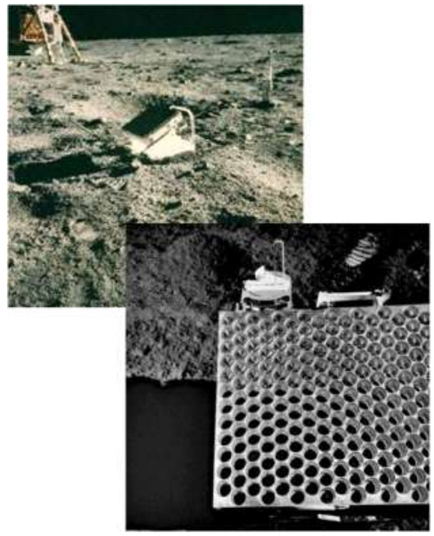
but if we rearrange this we have

$$\begin{aligned} &\theta_1 + \theta_3 + \theta_2 + \theta_4 \\ = \ &90^\circ + 90^\circ = 180^\circ \end{aligned}$$

or the outgoing ray is sent back toward the source! If we do this in three dimensions we have a corner cube. Here is a picture of a radar corner cube array.

Radar retroreflector tower located in the center of Yucca Flat dry lake bed. Used as a radar target by maneuvering aircraft during "inert" contact fusing bomb drops at Yucca Flat. Sandia National Laboratories conducted the tests on the lake bed from 1954 to 1956. (Image in the Public Domain in the United States)

And we left visible corner cube arrays on the Moon so we can bounce laser beams off of them and monitor the Earth-Moon distance.



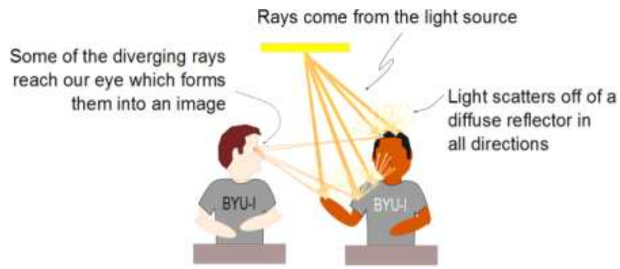
Apollo Retroreflector (Images in the Public Domain courtesy NASA)

Question 223.13.9

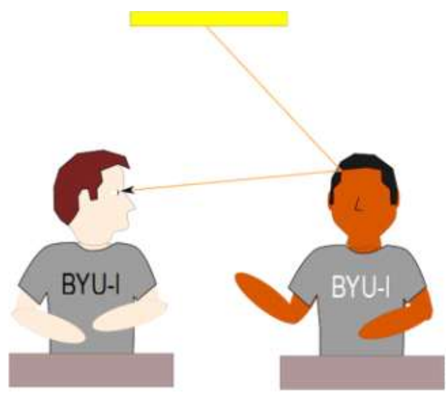
12.5 Reflections, Objects, and seeing

Armed with the law of reflection, we can start to understand how we see things. Using the ray concept, we can say that a ray of light must leave the light source. That ray then reflects from something. Suppose you look at the person sitting next to you in class. We should wonder, how is it that we can see them? We can only detect (see) light that gets to our eyes. Let's trace the light from it's source (the light fixture in our room) to our eyes to see how we see our neighbors.

Light comes from the ceiling lights and goes in all directions. Some of that light hits our neighbor. And some of that light that hits our neighbor will reflect. But is the person a specular or diffuse reflector? Once again, we can only give an answer relative to the wavelength of light. For visible light, your neighbors do not look like mirrors. The are diffuse reflectors. Light bounces off of them in every direction. Some of that light that reflects from your neighbor reflects in the direction of your eyes. That light can be detected. Your eye is designed to take this diverging set of rays and condense it into a picture of the person that your brain can interpret.

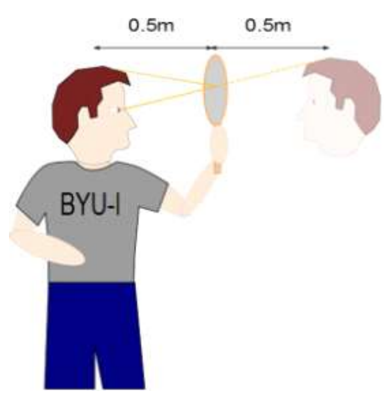


We tend to not draw the rays that bounce off the diffuse reflector but that don't get to our eyes, because we don't see them. So a ray diagram is usually much simpler.

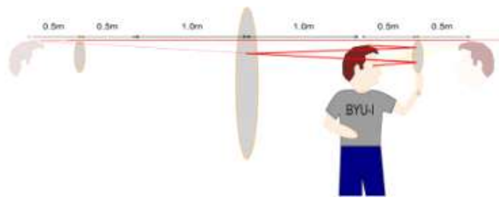


This is easy to understand, but we must keep in mind the wildly fluctuating superposition of waves that is masked by our macroscopic view.

We can use the idea of a ray diagram to solve problems. Suppose you hold a mirror half a meter in front of you and look at your reflection. Where would the reflection appear to be?



Knowing that rays travel in straight lines and that our mind interprets rays as going in straight lines, then we can use rays to see where the light appears to be from. The image is half a meter behind the mirror. Now suppose we look at an image of that image in a mirror behind us.



The ray diagram makes it easy to see that the image will appear to be 2 m behind the big mirror. You might not feel that this was so easy, but you might find it is not so bad in a problem in your near future.