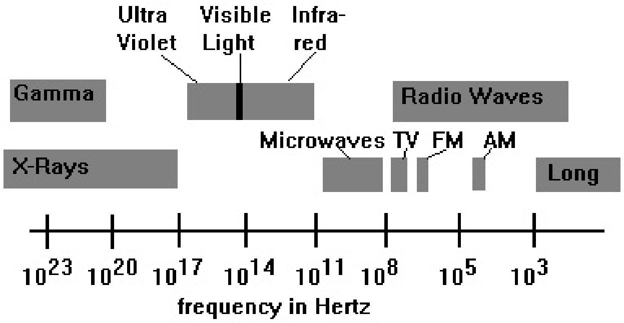
Chapter 33: Light Waves

What is Light?

Throughout our discussion of waves, we have occasionally been mentioning that light is a wave and that it behaves just as other waves do. However, we have never discussed exactly what it is about light that convinces us it is a wave. Since the time of the ancient Greeks (and even earlier) people has wondered and theorized about the nature of light. We know it is all around us, and we know that it can be controlled, but when you stop to think about light, it is actually a very puzzling phenomena. Isaac Newton attempted the task of explaining the nature of light, by saying it was a bunch of little particles that flew off of things and behaved according to the rules of mechanics. A short while later, a man by the name of Christian Huygens argued against Newton's theory by saying that light was actually a wave. Huygens's theory was not readily accepted by other scientists, but little by little more evidence mounted to support the notion that light was a wave. It wasn't until nearly two hundred years later that Heinrich Hertz demonstrated that light is indeed a wave and in fact there were many different forms of light waves. In this chapter, we will examine briefly the nature of light according to what is known today and then take a look at why we believe light is a wave (although I should take this moment to change the wording on that sentence; it should say "light can be described as a wave" for reasons that will be made clearer later. The student might want to take a moment and think about the distinction between the two sentence).

Today we believe that light is a wave and we also know that light comes in many forms. When we use the word "light", our mind usually immediately forms the image of light coming from a flashlight or a lamp. However, light in this and the following sections refers to any electromagnetic disturbance (more detail about just what that is later). Using this definition, such phenomena as x-rays, radio waves and microwaves are all light. The defining characteristic of light is its frequency. X-rays and visible light are actually the same thing, the only difference is that x-rays have a higher frequency. In fact, visible light makes up a very small portion of the entire electromagnetic spectrum.

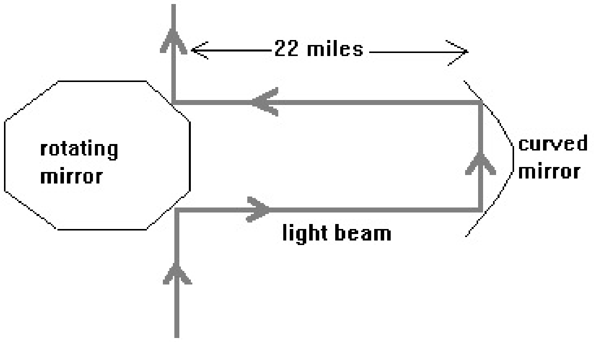


All of these light waves have different frequencies, and this allows for the different behavior that we expect from these waves in our everyday life. But they are all the same thing; electromagnetic disturbances.

But what exactly convinces us that all of these phenomena are the same, and besides that, in the first place that they are all waves? The answers come from a number of sources. If light is a wave it must meet a number of criteria: it must have a finite speed, something must be making up the wave, something must be oscillating and the wave must behave as other waves do.

The first of these criteria was a difficult task to establish. It was assumed, as early as Galileo, that light must have a finite speed (before then it was assumed to move infinitely fast, arriving at all locations the same instant it was produced). However, as you can imagine, the speed of light is very fast. Galileo himself set out to measure the speed of light by having a friend unveil a later on top of one hill while he was stationed on the other. His conclusion: "the speed of light is very fast" (which as basically all that could be concluded from such rough experimental procedures). From that point on, a number of scientists attempted to measure the speed of light, using different techniques. Two techniques that were note worthy was an attempt by XXXXXXXX to measure the speed by observing the moons around Jupiter. This gave a rough value of XXXXXXXX. The next attempt was by a man named Fizeau in 1849 who arrived at a value of 315300 km/s by using a rotating mirror. His technique was brilliant and the idea for the experiment sparked an interest in the mind of Albert A. Michaelson, an American teaching at the U.S. Naval Academy in Annapolis. Michaelson was a perfectionist and devoted his life to making precision measurements. He is considered to be one of the greatest American scientists and one of the best experimentalists in the world (he died in XXX). In fact, he was the first U.S.

citizen to win the Nobel Prize in Physics. His technique was borrowed from Fizeau but the precision and scale of the event were his own. What he did was to position two pieces of apparatus on top of two mountains, 22 miles apart. The first piece consisted of a rotation mirror and the second of a curved mirror.



The set up worked as follows. The light would strike the rotating mirror, bounce off, go across to the curved mirror and come back. During that time, however, the mirror was rotating and the light would only hit and reflect properly if the mirror had rotated <u>exactly</u> one eight of a turn (or some integer multiple of one eight). What Michaelson did was to vary the speed of the mirror until the light hit exactly properly. Then he know that the time for one eight of a rotation matched the time it took the light to travel 44 miles (there and back again). Naturally, the mirror needed to be spinning at an incredible rate. In fact, his first two rotating mirrors spun so quickly that they flew apart. In order for this procedure to work accurately, two quantities must be know with great precision: the distance between the two mirrors and the speed of rotation of the spinning mirror. The U.S. Coast and Geodesic Survey measured the distance between the two mountains to an accuracy of one-quarter of an inch and Michaelson measured the speed of the mirror in a number of fashions to be sure of an accurate reading. His results for the speed of light came out to be: c = 299729 km/sec (the abbreviation c is used from the Latin word celer, meaning fast). We do know that light travels different speeds in different materials and so Michaelson next measured its speed in a vacuum.

Today, we take a different approach to measuring the speed of light. We <u>define</u> it. We have defined the speed of light in a vacuum to be 2.99792458×10^8 m/s (for most problems you will simply use 3.00×10^8 m/s). This now means that velocity is a defined unit, and length is a derived unit. If we ever measure the speed of light more accurately, we will change the length of a meter so that the above speed still holds true. Obviously the speed of light is a very large number, but how fast is it? It is sometimes hard to get a grip on numbers that large, so let us take a look at some times for light to travel:

Number of times around the earth in one second: 7.5
Time to travel from the moon to the earth: 1 sec
Time to reach the earth from the sun: 8 min
Time to reach earth from center of the Milky Way: 63,000 years

Another good illustration of how quickly light can travel is that it is possible to listen to a concert in the back seats of a stadium and if you are listening to the same concert on the radio, you will hear each word and note through the radio before it will reach your ears traveling by sound waves across the stadium. Thus the sound, once converted to light waves in the radio station still travels fast enough to overtake the sound waves.

Once it was determined that light had a finite speed (something that was actually accepted before Michaelson made his fantastic measurement) the next question to ask is that if light is a wave, then what is waving and what is it traveling through? There really wasn't a good answer to the first of these questions until James Clerk Maxwell compiled his list of equations for electromagnetism. In compiling these equations, he noticed that manipulating them produced two equations of the form:

$$\nabla^2 E = \varepsilon_o \mu_o (\partial^2 E/\partial t^2)$$

$$\nabla^2 B = \varepsilon_o \mu_o (\partial^2 B/\partial t^2)$$

Do not worry about the mathematical symbols, all you should know about these at this time is that E and B are not constants, but functions. They are three dimensional vector equations for the electric and magnetic fields. The ε_o and μ_o are the permeativity and permeability of free space that you might remember from our chapters on the electric force and the magnetic field. What Maxwell noticed and found amazing about these equations is that they were almost identical to what is commonly known as the wave equation. This equation states that any function, f, that obeys the equation:

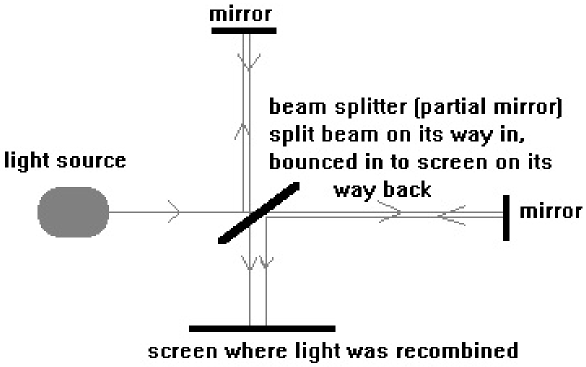
$$\nabla^2 f = k(\partial^2 f/\partial t^2)$$

is a function that describes a wave. Furthermore, it states that the constant k in the above equation is equal to 1/v, where v is the velocity of the wave. In Maxwell's equations, the $k = \varepsilon_o \mu_o$ and thus $1/\varepsilon_o \mu_o$ should equal the velocity of the waves. When he calculated $1/\varepsilon_o \mu_o$ he found it to be 3×10^8 m/s. The results of

Fizeau's experiment were well known at the time, and Maxwell concluded that the waves his equations described were light waves. It is hard to imagine the actual importance of this discovery. Maxwell was working on paper, not in a lab, and furthermore he was working with electricity and magnetism. Suddenly, he finds an unexpected result that tells him (mathematically!) that electricity and magnetism should produce waves. When he looks again he sees that waves should have the same speed as that of light, something that was still a mystery. Once again, two seemingly different areas of Physics were united and proved to be the same phenomena. Maxwell's work was not readily accepted in this instance. In fact, very few people took him seriously. The main test to prove him correct laid in the following situation. If light were electromagnetic waves, then there should be light other than visible light (which was all that was known at the time) and people should be able to produce these other forms of light in a laboratory and detect them. This was considered a challenge to all scientists: produce and detect light other than visible light. Most of the scientists of the day felt that this was impossible. Light is produced, like all other waves, by oscillating something, in this case an electric particle. They knew from the calculations that they would have to produce extremely rapid oscillations to produce light (frequencies of at the least 10^3 Hz. Nevertheless, one scientist succeeded. His name was Heinrich Hertz and he produced and detected the first radio waves which verified Maxwell's predictions (the experiment was modest according to todays standards, he was only able to detect them across the lab). It seemed that light was an electromagnetic wave after all.

Before we delve a little deeper into exactly what an "electromagnetic wave" is, we should spend a short bit of time talking about the last question mentioned above. Once it was verified that light was an electromagnetic wave, physicist began asking "What is it traveling through?". Consider a sound wave. In that case it is a wave of energy, or pressure, that travels through air. Scientists knew that light waves traveled through the vacuum of outer space, but they didn't know how. Every wave needed a medium (that was the thinking at the time) and no one knew what that medium was for light. Eventually, they did find a solution. For a myriad of other reasons, scientists believed that there existed a thing called "ether". This was a colorless, odorless, massless, completely stationary fluid that existed everywhere (including inside materials). The ether was formless, like a ghost, you couldn't scoop up a handful of ether, it would pass right through your hand as you tried. There were some good philosophical reasons for postulating the existence of this stuff, but absolutely no good scientific evidence that it existed. Nevertheless, scientists believed it was there. They theorized that the ether was the medium through which light traveled. It seemed a reasonable assumption.

If light were traveling through the ether, and the earth was traveling through the ether, Michaelson assumed that he should be able to measure the earth's speed through the ether by using the motion of light as a measuring device. He (along with a partner, Joseph Morley) developed an interferometer, one of the most sensitive devices ever developed. What it did was split up a beam of light, send a portion of it down two separate paths and recombine the light at the end. If the two paths were equal, the two light beams would arrive in phase and produce constructive interference. If they arrived out of phase, it meant that the paths were of different lengths. Michaelson and Morley made sure the two paths were of equal length and the instruments was so sensitive that he had to float it in an enormous tub of mercury on a XXXX ton concrete slab because working in the basement of a large building, the machine was disturbed by people walking on the sidewalk outside.



They reasoned that if the earth was flowing through the either in one direction (say left to right) and the light was a wave in the ether, it should take longer for the wave that originally goes through the beam splitter to reach the screen. Imagine the light as a swimmer in a current from right to left. The straight beam would be against the "current" on its way to the first mirror and with the "current" on its way back. The other beam would be perpendicular to the current the entire time. What the two experimentalists expected to see was a destructive interference pattern from which he could determine the speed of the "current" of the ether. When they tried the experiment, they say no destructive interference pattern. At first they thought that the experiment was not precise enough, but when they adjusted one of the arms an interference pattern arose, telling them the equipment was fine. Michaelson spent many years after that attempting to refine his device. Although he refused to admit it, his device was fine. The experiment failed because there was no such thing as ether.

The Michaelson-Morley experiment was one of the most important in modern physics and is a perfect example of a "failed" experiment teaching something very important. The fact the ether did not exist, came as sort of a shock to the scientific community. It was eventually, however, accepted. The results of this acceptance is that we now know (or believe) that light is a wave that can travel through a vacuum, it does not need a medium. But the implications went much further than that. It was mentioned earlier that the ether was needed for other philosophical reasons. Without the ether, those suppositions could be questioned and their questioning led to the acceptance of Einstein's Special Theory of Relativity (it is still debated whether Michaelson's results <u>led</u> to Einstein's formation of the theory or whether they just supported the theory after its formation). Indeed, the famous Michaelson-Morley experiment is considered to be the first experiment of the great revolution in modern physics. It was when the ancient and almost mystical idea of the ether was thrown out and new theories blossomed, taking physics to levels never dreamed of before.

Electric and Magnetic Fields and Light Waves

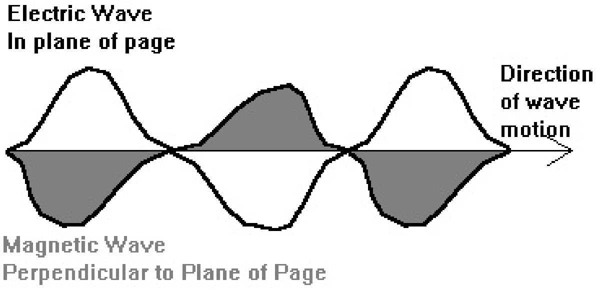
Maxwell told us what light waves were, Hertz showed us that they could be produced, and Michaelson and Morley inadvertently showed us that there is no ether. Yet we still haven't answered the question completely of what exactly light waves are. Light waves are electromagnetic disturbances that propagate out from a source.

Imagine a single electric charge, sitting stationary in empty space. Around that charge exists an electric field, as represented by Faraday's lines of force. If you were to suddenly move that charge up and then down again, you might imagine that the field around it would change. Imagine the field lines to be strings and envision what would happen. A short pulse would be sent out along the strings, just like a wave. This is exactly the situation that occurs in the field, a disturbance travels out from the charge (at the speed of light) and that electric disturbance <u>is</u> light. If we think back to Maxwell's laws and the principles of electromagnetism, we remember that a changing electric field will produce a magnetic field. Thus as we send out our electric pulse, a magnetic one is also created. Further, we also know that a changing magnetic field will produce an electric field, thus another electric field is created along with another magnetic field, an so on and so on. A light wave is this structured disturbance of electric and magnetic fields, continually creating each other as they travel.

Since the wave is actually a field disturbance, and not a material disturbance, it can travel through a vacuum, just as gravity or electricity can travel through a vacuum. To be more precise, a continual light wave (not just a pulse, as described) consists of two fields, an electric and a magnetic one, that travel together. A number of things are know about this arrangement:

- The electric and magnetic waves are standard sine and cosine waves.
- The two wave are perpendicular to each other.
- The two waves are transverse.
- The two waves are in phase.

If we would attempt to draw this, it would look like this:



In this drawing, the magnetic wave is perpendicular to the plane of the page (coming in and out of the paper). Notice how all the above statements hold true. As was stated earlier, this wave is "self perpetuating", meaning that unlike a mechanical wave, where the wave moves because of an elastic property of the material, this wave moves because the electric part produces the magnetic part and it begins a chain reaction. Since this is a highly efficient process, light waves can travel infinite distances without dying off (witness the light from the stars that reaches earth every night), unlike sound waves, which quickly lose energy due to the second law.

We can relate the amplitudes of these waves to the overall energy produced by a light wave. We should recall that the intensity of a wave is given by:

$$I = P/4\pi r^2$$

Where P is the power of the source, and r is the distance from the source to the point in question (the student should refresh their memories regarding the nature of intensity and the differences between it and energy). It should also be noted that this equation only applies to a point source of waves, producing spherically symmetric waves that travel freely in all directions.

For light waves, the intensity of a wave can be related to the electric and magnetic field amplitudes by a quantity called the Poynting Vector. This is a vector that gives the intensity at an instant and points along the direction of motion of the wave. It is found by:

$$\underline{S} = (1/\mu_o)(\underline{E} \bullet \underline{B})$$

and the student should know that E and B are related by:

$$E/B = c$$

Thus the Poynting Vector's magnitude is:

$$S = (1/\mu_o c)(E^2).$$

However, this equation only gives the intensity at an instant, since the E and B values are constantly changing (by a sine function). If we want the average power given over a period of time, we must use an average value for the E and B waves amplitude. The average amplitude of a sine function is found by:

$$A_{av} = \sqrt{2}A_{max}$$

Thus the average intensity of a light wave is given by:

$$S_{av} = (2/\mu_o c)(E^2)$$

EX. RDE.) What is the amplitude of the E and B waves coming from a 60 W light bulb when you are standing 2 m away?

With such a relation, we can actually determine the amount of energy delivered by individual wave fronts to a specific location. Consider that the Poynting vector gives us the average intensity at a location. We know that if given a specific amount of time and a certain amount of area, we could determine the amount of energy that the area received (since intensity is power over area and power is energy over time). It is also possible to determine the number of wave fronts that have struck that area during that time.

EX. WMIGH:) Determine the average energy per wave front that strikes a 1 m^2 area on the equator. Assume the intensity of the light from the sun is about 100 W/m^2 and the light has an average wavelength of 750 nm.

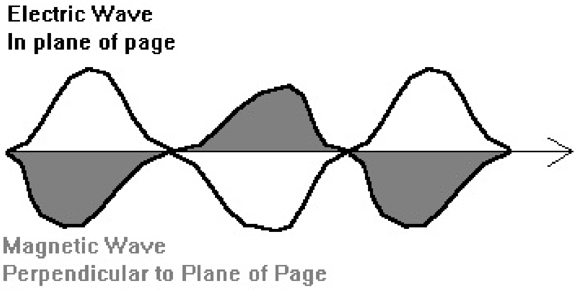
This problem underscores the importance of knowing the difference between amplitude, intensity and power. Comparing two different waves of the same amplitude, it would follow that they give different intensities and powers because a different number of waves are passing per second. Thus intensity and power are frequency dependent, yet amplitude is not.

Before we continue our investigation of light as a wave, there is one other wave phenomena which should be mentioned, as it will be important later. Imagine that you wished to impart energy onto a surface by means of absorbing light. However, there is a catch in this situation. You must deliver a very specific amount of energy in a very short period of time (say in the time it would take to absorb three or four wave crests) In that case, any amount of energy could be delivered to the surface instantaneously by simply changing the value of the amplitude of the wave. True, because high frequency waves have more waves per second, it might be easier to deliver energy more quickly by using higher frequencies, but we should still be able to deliver enough energy by using any wave, even a radio wave, if the amplitude was high enough. Strangely enough, there is an experiment (to be discussed in detail later) that shows that this is not the case. It was one of the major experiments that demonstrated that light cannot be completely described as a wave (and the solution earned Einstein a Nobel Prize in Physics).

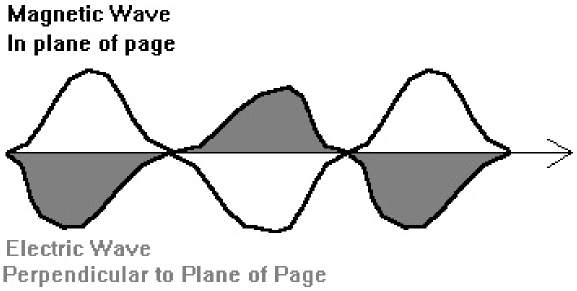
Polarization

To finish up this chapter, I would like to introduce the student to two other wave behaviors that distinctly point to light being a wave. Yet again, I will emphasize that all waves demonstrate these behaviors, however, some behaviors are more easily recognizable in certain waves. For example, beats can be produced by light waves, but they are difficult to make and detect. In the same fashion, these next two behaviors are common to all waves (actually, the first is unique to transverse waves) but are most obvious when dealing with light waves.

Polarization is a term that refers to the direction of vibration of a transverse wave. When discussing light waves, it is common to describe their plane of polarization as the plane in which the electric portion of the wave vibrates. A vertically polarized wave would look like this:

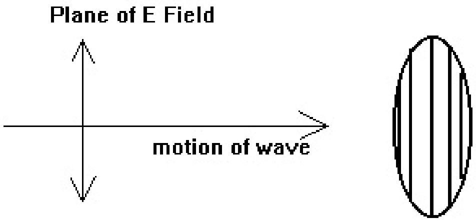


While a horizontally polarized wave would look like this:

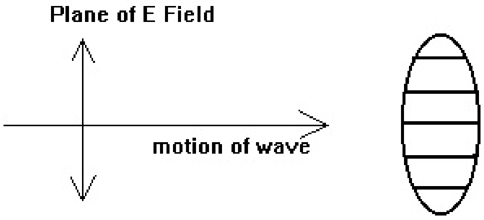


In general, light is rarely produced by one individual interaction (for example, light from the sun is produced by billions of billions of interactions and even light from a light bulb is made by the many different atoms in the filament). Therefore, most ordinary light is what we call "randomly polarized" meaning it contains many different light waves, each with their own, random polarization. However, sometimes light that is made under certain circumstances (by reflection) or light that is made by certain methods (TV and radio waves) can have one individual polarization. TV and radio waves are made precisely by antennas, which determine their polarization. If you have ever noticed, TV antennas in the United States are all horizontal, since TV waves are broadcast horizontally polarized. In Europe, they are broadcast with a vertical polarization, and thus the antennas there are set up in the vertical plane.

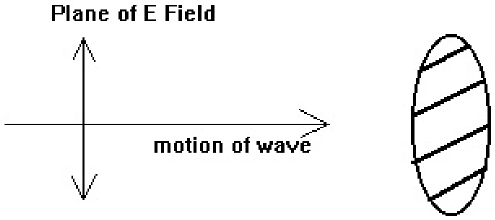
By using materials called "polarizers" we can manipulate the behavior of light waves using their polarizations. Polarizers are simply materials with very, very, very time slots that run across the material in one direction. For example, in the picture below, we have a polarizer that has vertical slots and light that is vertically polarized:



(In reality, the slots in the polarizer are only a few atoms thick). In this case, we can see that the light should be able to pass through the material without being hindered. However, in the case below:



None of the electric wave should be able to get through (and if no electric wave gets through, then no magnetic wave will be produced). Thus we have effectively "stopped" the light as if it had hit a wall. However, what happens in this situation?



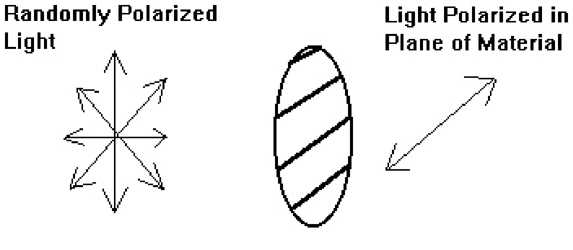
In this case, a portion or component of the wave will be allowed to pass through the polarizer. In fact, the amount of energy that can get through is given by:

$$E_{transmitted} = E_{incident}\cos\theta$$

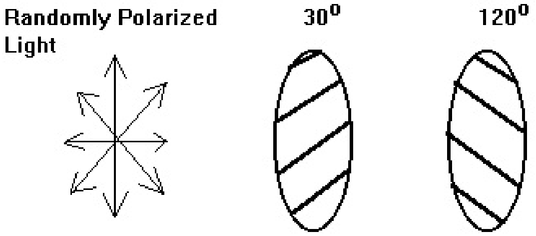
Where θ is the angle between the plane of polarization and the slots of the polarizer (which is simply the component of the polarized wave that lies along the lines). However, when dealing with light we are mostly concerned about the intensity, not the energy. Since $I \propto E^2$, the intensity equation is:

$$I_t = I_i\cos^2\theta.$$

This is one of the main uses of polarized materials. Since most light is randomly polarized, it looks like this:

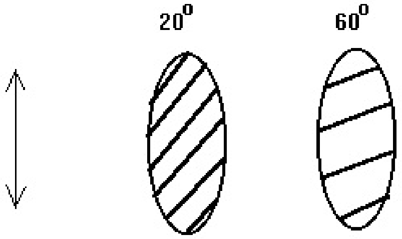


In this case, unpolarized light struck the material and only light that was in the direction of the slots was allowed to pass through (along with components of all the other light that lay in the direction of the slots). Thus it turned unpolarized light into polarized light. Now, what would happen in this scenario (all angles are given from the vertical line)?



In this case, no light would emerge from the other end, since the first material would polarize the light at 90° to the second polarizer.

EX. TBG:) What would be the percentage of intensity that made it through the set up of polarizers below ?



Polarizing materials can be made by using very long polymers (chain like carbon molecules that can sometimes be thousands of atoms long). The material is stretched, thus causing the long molecules to line up in rows, much like stretching a batch of mixed up strings. We often hear about "polarized sunglasses" that reduce glare while driving. It turns out that when light is reflected off of a surface, it can often end up being polarized parallel to the surface. Thus light that bounces off the back of a car is often horizontally polarized (or at least a good portion of it). Sunglasses are often made with the slots vertical, so this type of light (called glare) does not reach your eyes.

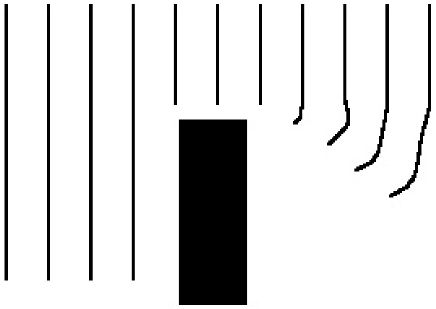
Another interesting thing is that sometimes polarization will affect some colors of light and not others. If you take a thin piece of clear plastic or a thin glass object and view it though polarizers, you might notice a dazzling display of different color light (like the patterns made by oil on a puddle on a sunny day, but for different reasons). This is because different amounts of stress in the material will cause it to polarize different colors of light. What you are actually seeing is a "stress pattern" showing the forces that exist in the material itself. Sometimes this is used to determine if certain clear materials are damaged or have imperfections in their manufacturing.

In short, because light appears to be polarized and can be manipulated by polarizing materials, we have further proof that it behaves like a wave.

One last mention should be made of another situation where polarization occurs and that is polarization by reflection. Although the statement and phenomena are easily understood, it is very important and shows up in a number of different physical situation. To put it succinctly, when a wave strikes a barrier and some is reflected, the reflected part of the wave becomes polarized **parallel to the plane of the surface**. A perfect of example of this in action is polarized sunglasses and driving a car. When driving, some of the most distracting and annoying light comes from the reflections of the sun off of other cars (windshields, chrome bumpers, etc.). But since the light in those cases is being reflected, it is usually polarized. Since the surfaces of reflection are generally horizontal, so is the plane of polarization of the most annoying light. Sunglasses are polarized vertically, thus cutting out the unwanted glare.

Diffraction

The next wave behavior that light exhibits is diffraction. Consider a flashlight with a very small opening for the light to escape. If you point that flashlight at a wall, the circle made will be larger than the opening for the light. This makes good, logical sense (why?). However, the circle made on the wall will not have sharply defined edges. The same problem can be illustrated by holding a pencil in front of the flashlight. You will get a shadow of the pencil, but the farther away the wall is, the less defined the shadow will be. What you are seeing is an effect called dispersion. Diffraction is when a wave spreads out after passing a barrier. The result is illustrated below.



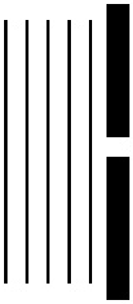
This is the reason that the circle on the wall is not well defined, the waves are spreading out and "washing out" the edges. It also explains the lack of a well defined shadow at a distance, since the waves are in essence merging back together after they pass the object (an astute student might ask, "What about a laser pointer? Doesn't that diffract? Yet it manages to produce a well defined circle." The answer is yes, it does diffract, but laser light is a special kind of light called coherent light, which will be explained later. One of the properties of coherent light is that it diffracts very little). It also explains how it is possible to hear a person around a corner. If the sound waves didn't diffract, the sound would go right past the barrier and someone standing right on the other side of the wall would not hear it.

The amount of diffraction that occurs depends on a number of factors, namely the wavelength of the waves and the size of the obstacle. This can be illustrated with a thought example involving the ocean. Imagine that you put a large tractor trailer truck in the ocean about 30 feet from the shore. By observing the waves that reached the beach, you would be able to tell that something was there. Now imagine putting a pencil at the same location. Do you think you would notice a difference in the wave pattern at the shore? This leads us to an important conclusion about diffraction:

> If the obstacle is small compared to the wavelength, the diffraction is great, meaning a shadow is indistinguishable.

This phenomena illustrates what I call the "Wavelength Problem" for viewing atoms. No matter how great our scientific and technical knowledge advances, we will never get a true picture of an atom. The pictures you see in books are actually electron microscope "pictures" and they only show us in added, false color, what happens when a stream of electrons shower past atoms and react with them. Although the stream of electrons behaves like light, there is not guarantee that light would behave exactly the same. A picture of an atom would require us bouncing light off the atom and somehow having it reach our eyes. However, atoms are much smaller than visible light, thus because of diffraction we will never "see them", the light will just wash over them. If we attempt to use smaller wavelength light, it will get more energetic and end up knocking the atom away instead of bouncing back to our eyes or our camera. No matter how good our microscopes get, we will never truly see an atom.

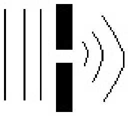
Diffraction also occurs from small openings, commonly called slits. If a wave strikes an opening, after passing through, it will begin to diffract as in the diagram below:

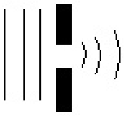


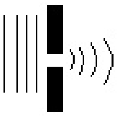
The amount of diffraction is governed by two rules:

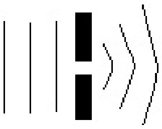
- The narrower the opening, the greater the diffraction.
- The longer the wavelength, the greater the diffraction.

This is illustrated by the diagrams below.

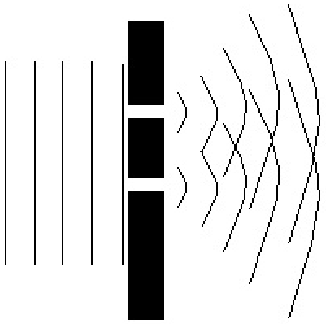




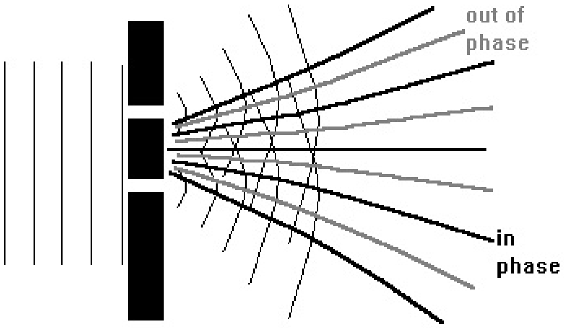




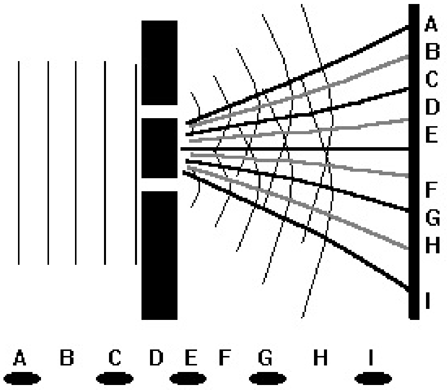
This diffraction can be seen if you cover a flash light with aluminum foil and poke a hole in the center. Once again you will not get a defined spot of light on the wall. But one of the most interesting applications of this phenomena comes from what is called the "Young's Double Slit Experiment", which is yet another strong proof that light behaves like a wave. The way the experiment works is that a wave is incident on a barrier with two small slits cut into it (It is important to note that for diffraction to be noticeable, the slits should be small, less than the wavelength). As the waves pass through, they begin to diffract and create circular waves. This is actually a method of producing two identical waves that are precisely in phase (and it is the problem alluded to in a previous chapter when a sample problem like it was done). We end up with a pattern like this:



Notice how the wave crests all line up one a straight line in the middle. Think for a moment about what this would mean. Since that line represents a line where every point is the same distance away from both slits, the waves will always arrive there in phase. If we examine the entire area, we will find that there are lines (or actually curves) where the waves will always arrive in phase and other curves where they will always arrive out of phase. Mathematically, these curves can be found to look something like this:



The lines along which the two waves arrive in phase are called anti-nodal line and the lines where they arrive out of phase are called nodal lines. Our knowledge of waves tells us what will occur at these lines. The anti-nodal lines will be areas of constructive interference and the nodal lines will be lines of destructive interference. Now imagine that a screen was placed in front of the pattern as shown. If this pattern was produced by light, what would you expect to see? You would end up seeing bright and dark spots on the screen corresponding to constructive and destructive interference. The pattern is also shown in the diagram, with letters corresponding to each point.

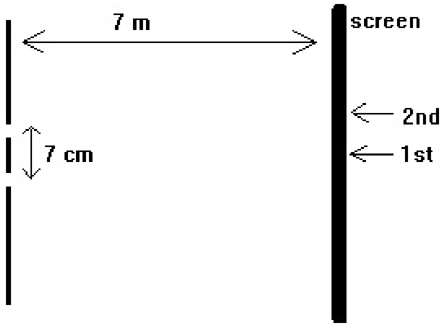


It is interesting to think about what this would correspond to in the case of sound waves. In actuality, this can be illustrated using two stereo speakers, provided they are placed the proper distance apart and only a <u>single, pure tone</u> is sounded from them. If the wavelength is constantly changing (as in the case of a song) the pattern will change also.

To observe these interference patterns in either light or sound, one condition must be met: the two sources (or slits) must emit exactly the same waves in phase at those points. To produce this requires some care and thought.

Although these patterns can be treated mathematically, to do so is cumbersome and complex. Instead we leave it to the student to grasp just the conceptual understanding of diffraction patterns and to be able to apply those to solve some simple mathematical problems.

EX. OIUN:) On the set-up below, the first anti-nodal line is formed in the middle and the second line is formed 5 cm away. From the information given, determine the wavelength of the light being used.



EX. IUJY:) Discuss and draw the different diffraction patterns that would result from changing the waves used to a.) smaller and b.) larger waves.

Another interesting thing to consider is how the pattern would change if the two slits produced light that was exactly out of phase.

These interference patterns show up in "the real world" in a number of situations, three of which are mentioned below.

- These types of patterns can show up whenever any two sources emit waves that are identical. In these cases, the waves are spherical, thus the nodal and anti-nodal lines emanate in all directions. This can occur with CB antennas on tractor trailer cabs. They will actually produce "dead zones" (nodal lines) in some areas around the vehicle, where their broadcasts cannot be picked up. Careful placement and spacing is needed to make sure as few nodal lines as possible fall in front of and behind the vehicle. Because of this, it is not recommended that CB antennas be used in pairs on pick-up trucks, since they are thinner and would change the diffraction pattern.
- Diffraction patterns can result from placing a thin wire in front of a laser beam (acting as the spacing between the two barriers). If the wavelength of the bean is know, it is possible to determine the thickness of the wire very accurately by measuring the spacing between the anti-nodal lines on a distant screen.
- Diffraction patterns can be made by passing light through a three dimensional lattice, each point on the lattice acting like a small barrier. The patterns that form are usually circles, not dots, but by examining them, the lattice properties can be determined. This is done using x-rays and thin slices of materials and it can tell us much about how the atoms are arranged in a materials lattice.

To conclude, the importance of diffraction and diffraction patterns is that is persuades us that light does indeed behave like a wave. In fact, it was Young who first put forth this experiment to verify Huygens's wave theory of light and it was one of the first experiments to refute Newton's theory that light was tiny particles instead of waves. When this theory was put forth, a supporter of Newton, Poisson, posed an interesting question to a supporter of the wave theory, Fresnel.

Fresnel's Bright Spot

He said consider blocking the path of a light beam with a small sphere, like the head of a pin. Imagine the shadow of the sphere on the wall and look at the center. Logic tells us at first glance that the center should be the darkest spot of the shadow. However, if diffraction is correct, the two waves should bend around the pin and meet in the center in phase. We should see a bright spot in the center of the shadow. Although this can't be noticed with a regular flash light, Fresnel's Bright Spot is visible with a laser or other powerful light source. Once again, the critics are silenced and light appears to be a wave.

Assignment #33

1.) For each of the types of light listed below, find the wavelength that corresponds to each frequency.

x-rays; $\nu = 3 \times 10^{20}$ Hz
blue light; $\nu = 6.31 \times 10^{14}$ Hz
yellow light; $\nu = 5.22 \times 10^{14}$ Hz
microwaves; $\nu = 3 \times 10^{10}$ Hz
radiowaves; $\nu = 3 \times 10^{8}$ Hz

2.) Using the explaination given in the chapter, derive an equation that would give the speed of light from Michaelson's (or Fizeau's) apperatus. Use the following variables: c (speed of light), n (number of 1/8 rotations made by mirror), ω (angular velocity of mirror), d (distance between mountains).

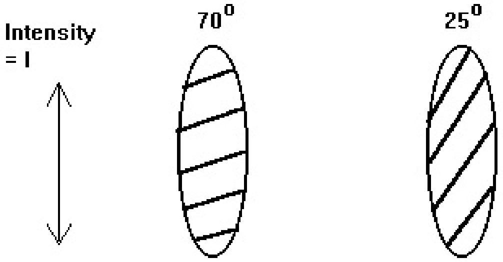
3.) In the chapter, an example was given where you were able to hear a sound transmitted through a radio before the sound reached you at a concert. If you were 250 m from the stage and the sound was immediately sent up (via radio waves) to a satellite that was at a 500 mile orbit (above the surface), what would be the difference in time between receiving the radio sound and hearing the actual sound?

5.) A microwave oven heats food by striking it with microwaves. How efficient is s 700 W microwave (electrical input rating) that can heat a 500 ml glass of water from 30° C to 100° C in 4 minutes? Assuming the efficency of electrical energy to microwave energy to be 80%, what is the intensity of the microwaves? What is the average value of the electric and magnetic field of these waves?

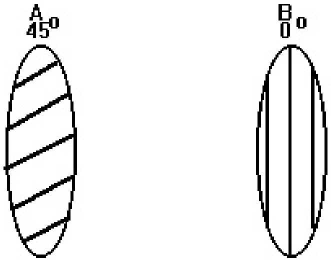
6.) If a radio station broadcasts at 50,000 W, what is the value of the electric and magnetic fields produced by the antenna at 3 m distant? What is the value of the Poynting vector at a distance of 10 miles? How much energy is received by your car antenna at that distance (assume the antenna covers a total area of 4 cm^2) in one second?

7.) If an x-ray source of wavelength 10^{-10} m is used at a dentist office, how much energy is absorbed by your body (and the film) in a one second exposure? Assume the affected area is about 80 cm^2 and you face is 75 cm from the source.

8.) If vertically polarized light strikes the set of polarizers shown below, how much of the original intensity comes out on the right hand side? All angles given are from the vertical.



9.) Horizontally polarized light with an intensity of 10 W/m^2 strikes the polarizers shown below. How much gets through if a.) only polarizer A is in place? b.) only polarizer B is in place? c.) both polarizers are in place?



10.) The set up below is used to form a double slit diffraction pattern using light of a wavelength of 745 nm. How far along the screen from the center is the next bright dot located (use approximation techniques)?