Chapter 3

WAVES IN GENERAL
and
LIGHT WAVES IN PARTICULAR

A.) Waves In General:

1.) As was pointed out a few chapters back, light can be characterized either as a wave or as a particle. To understand some of the wave phenomenon associated with light, we have to talk some about wave properties in general. The first few sections of this chapter will do that. From there, we will move off into topics related to light as a wave.

2.) In general, a wave is a disturbance that moves through a medium.

a.) Example: You can't have a water wave without water.

i.) Yes, this sound dumb . . . but it isn't. When a rock is thrown into a calm pond, the surface of the water is disturbed as the rock enters. That disturbance is what moves out away from the entry point.

ii.) In this case, water is the medium. The disturbance in the water is what moves through the water as a wave.

b.) Consider how a sound speaker works.

i.) A *sound wave* is a *<u>pressure</u> disturbance* that moves through air or water, or whatever the host medium happens to be.

ii.) The cone of a speaker is forced outward, it momentarily compress air molecules together creating a high pressure region. This region is accelerated outward away from the speaker.

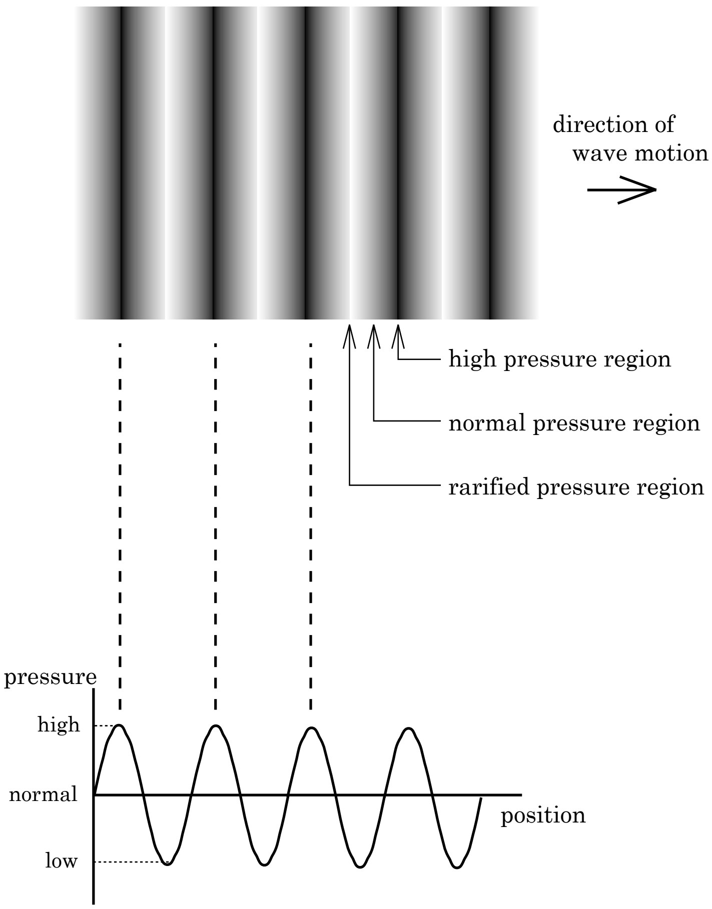
iii.) As the speaker cone pulls back, it passes through its equilibrium position on its way to momentary creating a rarefied region in which the air pressure is lower than usual. *This* region is accelerated outward away from the speaker.

iv.) As the speaker cone oscillates back and forth, it creates a region of high pressure, then normal pressure, then low pressure, then normal pressure, then high pressure, etc.

v.) The upper figure is a representation of what sound waves would look like if our eyes were sensitive to these very subtle pressure variations

vi.) The lower figure graphs *pressure variation* versus *position* for sound at a *given point in time*).

vii.) These *pressure disturbances* move out into the surrounding air at approximately 330 meters per second (i.e., the *speed of sound*). As they pass a hearing person, the pressure variations motivate tiny hairs in the listener's ears to vibrate generating electrical signals which, upon reaching the brain, are translated into incoming sound.



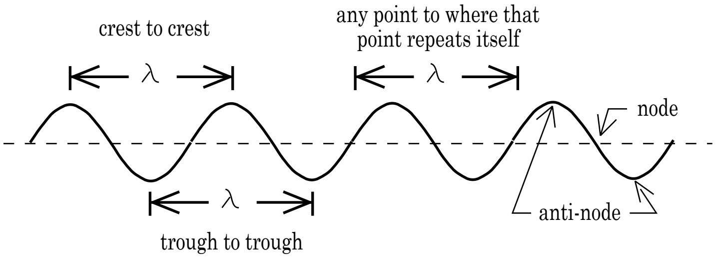
Pressure versus Position Graph for SOUND WAVES (at a given instant in time)

viii.) Again, sound waves are a *disturbance moving through a medium*. Without the medium, there can be no sound.

Note: What this means is that the next time you see *Star Wars* and they show a big battle scene viewed from space, and there are deafening explosions as attacking battle craft get blown to smithereens, you have every right to stand up in the middle of the movie theater and shout at the top of your lungs, "WAIT, WAIT, THIS CAN'T BE. THERE IS NO SOUND IN SPACE!!" They'll probably throw you out of the theater for causing a disturbance (i.e., for making waves--a little physics humor), but you will be correct in exposing one of Hollywood's greatest displays of scientific misinformation ever.

3.) Some quick definitions (some of this is review from last chapter):

a.) Wavelength (λ in meters): the distance between two successive crests, or two successive troughs, or between two successive positions along the wave that are exact duplicates of one another.



b.) Frequency ("ν" in cycles/second--this symbol is a Greek "nu"): the *number of wavelengths* that pass a fixed observer *per second.*

c.) Period ("T" in seconds/cycle): the *time* required for one full wavelength to pass a fixed observer. As in vibratory motion, $T = 1/\nu$.

d.) Wave velocity ("v" in meters/second): the velocity of a wave disturbance as it moves through its medium. Mathematically:

$$v = \lambda \nu .$$

(Don't believe me? Check the units.)

A consequence of this relationship: for a given wave, *high frequency* corresponds to *short wavelength* and vice versa.

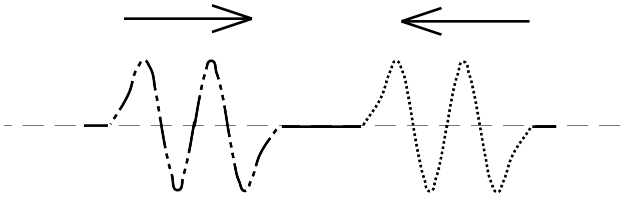
e.) Nodes and anti-nodes: a *node* is a null spot on the wave. It corresponds to a place where the displacement of the wave is zero. An *anti-node* is a spot where the displacement is a maximum. It corresponds to a crest or trough.

4.) Waves are important because they carry *energy*.

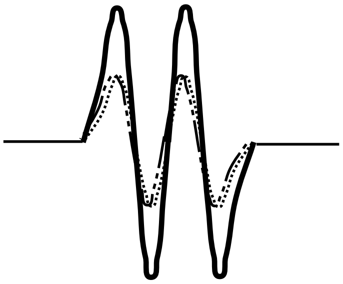
a.) If waves didn't carry energy, *sound waves* wouldn't have the wherewithal to wiggle those little ear-hairs that prompt the neurological response that your brain registers as hearing.

b.) If waves didn't carry energy, *tidal waves* wouldn't have the ability to blow away whole island-populations with a single achoo.

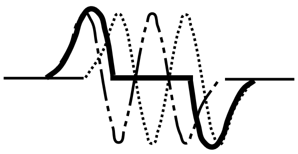
5.) When two waves in the same medium run into one another, the two disturbances will superimpose on each other linearly. Given such a situation, there are a number of outcomes:


original waves moving in opposite directions in same medium

a.) Constructive superposition (sometimes called *constructive interference*): A situation in which the two waves momentarily produce a single wave that is *larger* than the original two. For two waves with the same amplitude *A*, completely *constructive superposition* will yield a displacement of *2A*.


completely constructive superposition
(the dark line shows the net effect)

b.) Destructive superposition (sometimes called *destructive interference*): A situation in which the two waves produce a single wave that is *smaller* than the largest of the original two. For two waves with the same amplitude *A*, completely *destructive superposition* will produce a net displacement of zero.


partially destructive superposition
(central superposition is totally destructive)

c.) The sketches show two waves (one denoted with dots, one denoted with dots and dashes) moving in opposite directions in the same medium, and waves at various stages of superposition.

B.) The Doppler Effect:

1.) The Doppler Effect is the consequence of a *wave producing source* that is moving relative to a device that is designed to detect the wave (in the case of sound, that detecting device could be your ear).

2.) Consider a single sound source that puts out sound of wavelength λ_1. At regular intervals, a sound crest (i.e., a high pressure ridge) is emitted from the sound source and moves out at approximately 330 m/s (i.e., the speed of sound in air). The figures below show a progression of such crests. Note that the listener in the sketch hears sound whose wavelength is λ_1. The frequency of that sound, using $v = \lambda\nu$, is $\nu_1 = \frac{v_{sound}}{\lambda_1}$.

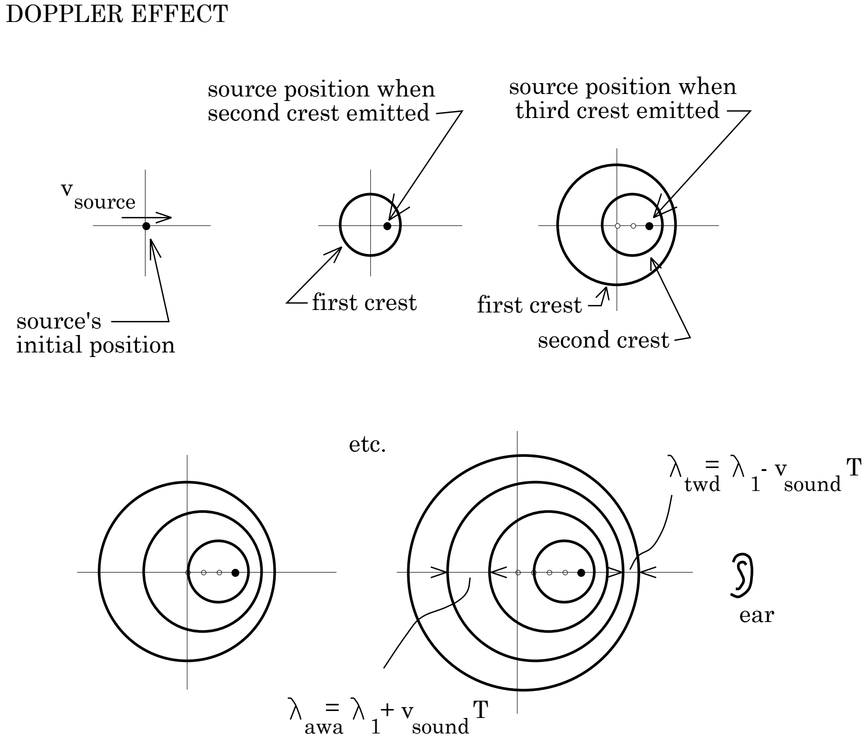
3.) What happens when the sound source moves toward the listener (or vice versa)? The sketch on the next page shows the situation.

a.) Assume that at $t = 0$, the sound source puts out its first crest.

b.) After a time interval equal to the *period T* of the wave (remember, the period is the time required for one cycle to pass by . . . it is also equal to $1/\nu_{source}$), a second crest is emitted.

c.) After another period's worth of time, another crest is emitted, etc.

d.) The distance between successive crests should be λ_1, but that is not what the listener perceives. Why? Because the sound source is moving toward the listener. As such, the distance between crests is smaller than λ_1 (look at the sketch).



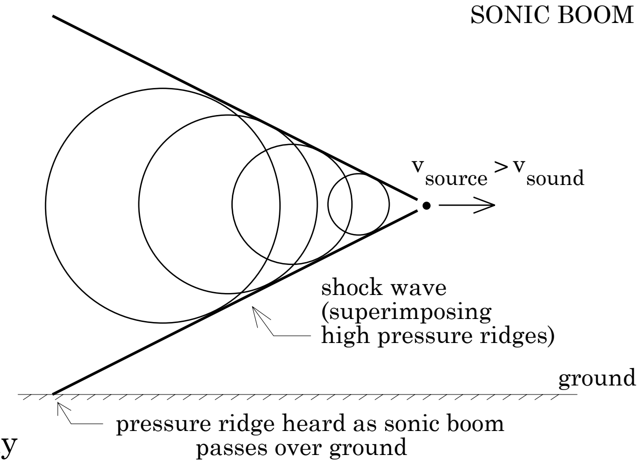
e.) A shorter wavelength corresponds to a higher frequency. That means the sound the listener actually hears is at a *higher frequency* than would have been the case if the source and listener were stationary relative to one another.

f.) The exact opposite happens when a source is moving away from the listener. The perceived wavelength is longer than the source wavelength (look at the sketch on the away side of the circles), which means the frequency is lower.

4.) On the optical light spectrum, the frequency of red light is lower than the frequency of blue light.

a.) As such, when a Doppler shift occurs that produces a perceived lowering of a light source frequency, the wave frequency is said to be *red shifted*.

b.) By the same token, when a Doppler shift occurs that produces a perceived increase in the light source frequency, the wave frequency is said to be *blue shifted*.



SONIC BOOM

Interesting Side Note: When the velocity of the *source* of a sound is *greater than* the velocity of sound itself, high pressure ridges superimpose in such a way as to stack up on themselves creating a single, super-high intensity pressure ridge (see sketch). This shock wave is what causes *sonic booms* when jets exceed Mach 1 (i.e., the speed of sound).

5.) The Doppler Effect is particularly useful in astronomy.

a.) White light is the superposition of all of the frequencies of electromagnetic radiation to which our eyes are sensitive.

b.) A prism (or, for that matter, a diffraction grating) can spread these superimposed frequencies out.

i.) This is why white light passed through a prism yields the colors of the rainbow.

c.) Stars give off white light, but for reasons that will be expanded upon in Chapter 5, stars "absorb out" certain frequencies of that light. That means that when star light is passed through a prism or diffraction grating, frequency gaps called *spectral lines* are observed.

d.) One particular gas, Hydrogen, is found in all stars. Because we have passed white light through Hydrogen here on earth, its absorption spectra (i.e., the series of spectral lines that are absorbed out when white light passes through Hydrogen) is well known.

e.) What is interesting is that when we look for the pattern of hydrogen spectral lines in light from stars, we find the lines in cooler stars, but we find them shifted toward the red end of the spectrum. That is, their calculated frequencies are *lower* than they should be.

f.) This is a Doppler shift. It is caused by the motion of the star relative to Earth. The shift is associated with light waves instead of sound waves, but the principles are the same.

i.) From the observed shift, we can deduce two things. First, as all star light seems to be red-shifted, all stars must be moving away from us (a shift toward lower frequency is observed when a wave source recedes from an observer).

ii.) Second, by measuring how large the red shift is, we can determine the speed of the star relative to the earth.

Note: For stellar objects in our galaxy, red shift is due to their motion in space, relative to us. For stellar objects outside our galaxy, red shift is due to *the expansion of the universe*. We'll talk more about this later.

C.) A Preamble to Understanding Light--Electric and Magnetic Fields:

1.) A question that often arises is, "If a wave is a disturbance that moves through a medium, and if light is a wave that is able to travel through the nothingness of space (think about it--the space between the earth and the Sun is nearly a vacuum), what is the *medium* through which light waves travels while in space?"

The answer to this question is based on an understanding of what light actually is. To understand that, we need to say a little about *electric fields* and *magnetic fields.*

2.) We will begin with the *electric field.* Let's assume you have a small metallic sphere. You place q_1*'s* worth of charge on it and place it immovable out in space. You take a second metallic sphere and place q_1*'s* worth of charge on it. You bring the second sphere in close to the first sphere. What will happen?

> **a.)** If the two charges are of the same type (i.e., both positive or both negative), q_2 will experience a repulsive force due to the presence of q_1.

Minor Note 1: In fact, q_1 will feel an equal and oppositely directed force on it due to the presence of q_2, but we are only interesting in here is how q_1 affects the space around it.

Minor Note 2: The unit of force in the MKS system is the *newton*; the unit of charge is the *coulomb*.

> **b.)** If the two spheres are oppositely charged, q_2 will experience an attractive force due to the presence of q_1.

3.) There is a function that defines the size of force on one *point charge* (i.e., a charge that resides on at very small point or on a body that can be approximately as a point). That function is called Coulomb's Law. Coulomb's Law reads:

$$F = k\frac{q_1 q_2}{r^2},$$

where the *q* terms are the respective charges, *r* is the distance between the charges, and *k* is a constant.

Note: The constant is equal to $\frac{1}{4\pi\varepsilon_o}$, where ε_o is the permittivity of free space--one of those universe constants set at the Big Bang.

4.) Somewhere along the line, someone decided it would be more useful to have a function that would state how much *force per unit charge* was *available* at a point, regardless of whether there was a second charge there to feel the force or not. Thus was born the idea of *the electric field.*

a.) An electric fields is a modified force field. As evaluated at a given point, its direction is defined as the direction a *positive test charge* would accelerate if put at the field.

b.) The magnitude of an electric field is defined as the amount of *force per unit charge* AVAILABLE at the point (whether there is a charge there to feel the force or not).

5.) For the specific situation in which the field producing charge is a *point charge*, this *force per unit charge* expression can be derived using Coulomb's Law (i.e., the force a point charge q_1 exerts on a second point charge q_2) divided by q_2. That is:

$$
\begin{aligned}
E &\equiv \frac{F}{q} \\
&= \frac{\left(k\frac{q_1 q_2}{r^2}\right)}{q_2} \\
&= k\frac{q_1}{r^2}.
\end{aligned}
$$

a.) Note that the final result for the magnitude of the electric field due to a point charge is dependent *ONLY* on the size of the *field producing charge* and on the distance *r* between the field producing charge and the point of interest. THERE IS NO SECOND CHARGE IN THE EXPRESSION!

b.) Note also that the unit for the electric field is *newtons/coulomb*.

c.) We aren't done with the idea of an electric field, but we have to look at another phenomenon before we can put everything together.

5.) A *magnetic field* is different from an *electric field* in the sense that electric fields are modified force fields whereas magnetic fields are *not*. (This should make more sense shortly.)

6.) The presence of a magnetic field is sensed with a compass. In fact, the direction of what is called the *magnetic field vector* is defined as the direction a *compass* would point if put in the field at the point of interest.

7.) It has been experimentally observed that if a compass is brought near a current carrying wire (i.e., a wire in which charge is moving), the compass will point in a direction *tangent to a circle centered on the wire*.

a.) First conclusion: *Charge in motion* is what *generates* magnetic fields.

b.) Second conclusion: Magnetic field lines *circulate* AROUND current carrying wires.

i.) The "current" that generates a magnetic field in a piece of iron is found in the spin motion of electrons in the iron's atomic structure. (I'll say more about this later.)

ii.) The earth's magnetic field is related to the flow of iron--a substance that is inherently magnetic--in the earth's core.

8.) How do we know that magnetic field lines are not modified force fields?

a.) Let's assume you are out in space (i.e., away from any gravitational fields). You pull out your compass and notice that it registers a magnetic field. Lets say the field is oriented from the right side of this page to the left. You pull a charge out of your pocket (we are being silly, again, but as always, play along) and put it in the magnetic field. What will the charge do?

What it will do is *absolutely nothing*. There is no gravity (you are out in space), and the magnetic field will not act like a force field. In short, the charge will just sit there.

b.) You nudge your charge so it moves to the left along the magnetic field lines. After the nudge, does the motion change the way as it would if there was a force acting on it along the magnetic field lines (i.e., will the charge pick up speed or slow down)?

Absolutely not. The charge will continue to move in the direction you pushed it with exactly the same velocity it had when you stopped applying your own push force.

c.) And if you shoot the charge *across* the magnetic field lines, what happens? THEN you will observe a force. That force, though, will be *perpendicular* to the direction the charge is moving, AND *perpendicular* to the line of the magnetic field lines.

Note: When a force doesn't change the magnitude of an object but does change the direction of the object's motion, that force is dubbed a *centripetal force.*

i.) Example: If the charge was moving directly into the page as it passed through the paper, the direction of the force at that point would be *upward* toward the top of the page. Notice that *upward* is perpendicular to the direction of motion (i.e., *into* the page) AND *perpendicular* to the magnetic field lines which are across the page to the left.

d.) There is a way to determine both the magnitude and direction of the magnetic force on a point charge that is moving through a known magnetic field, but for our purposes you don't yet need to know that so we'll end this here.

9.) The last couple of bits of information you need to know about magnetic fields are:

a.) Just as *electric fields* are symbolized by an *E*, magnetic fields are symbolized by a *B* (a weird choice, but NO JOKE).

b.) In the MKS units system, the unit for magnetic fields is *teslas*. In the MKS units system, the unit for magnetic *force* is, as is the case with *all* forces, *newtons.*

10.) NOW IT'S TIME TO PUT THINGS TOGETHER!

11.) Consider a radio antenna. What happens when an AC signal is impressed on the antenna?

Note: An AC signal generates a current that alternates back and forth. That is, charge moves in one direction, then reverses and moves in the other direction, then reverses and moves in the first direction, then moves in the other direction, etc.

12.) So we have this AC source attached to an antenna. Assume the first bit of charge that first runs up onto the antenna is *negative* (we're talking free electrons). As it does this, two things happen.

a.) The presence of free charge creates an electric field in the region around the antenna.

i.) Note that the direction of this electric field is inward *toward* the antenna.

ii.) How so? If you will remember, the direction of an electric field is defined as the direction of a *positive charge* would accelerate if put in the field and released. As *positive charge* will be attracted to the *negative charge* on the antenna, the direction of the electric field will initially be radially inward toward the antenna.

b.) As more and more electrons run up onto the antenna, the intensity of the electric field increases.

c.) At some point, the negative charge will stop running onto the antenna and will begin to drain off the antenna. As this happens, the electric field in the antenna's proximity will diminish.

d.) Once all of the negative charge has drained off, negative charge will continue drain making the antenna more and more electrically *positive* (from the outside, this would look just as though positive charge was moving *onto* the antenna--you can think of it either way).

e.) When this happens, the direction of the electric field reverses facing away from the antenna, and the magnitude of the field increases as the antenna becomes more and more positive.

f.) Once the positiveness hits its peak, it will begin to drop decreasing the magnitude of the electric field until the antenna is electrically neutral. At that time, the whole cycle will start again.

g.) In short, charge flowing onto and off of the antenna will produce a time varying, alternative electric field in the region of the antenna.

13.) The other thing that happens as charge moves up and down the antenna is that an time varying, alternating magnetic field is produced in the region around the antenna.

a.) Remembering that a magnetic field set up by a current carrying wire *circles* around the wire with the direction of the magnetic field being tangent to a circle centered on the antenna.

14.) Put together, all of this means two things.

a.) First, the direction of the electric field and magnetic field in the vicinity of the antenna will always be *perpendicular* to one another.

b.) The magnitude of the electric field and magnetic field in the vicinity of the antenna will change (alternate) in synch with one another.

c.) The frequency of the alternating electric field and magnetic field will be the same.

15.) Consequences?

a.) If the frequency of the fields is below 500,000 cycles per second, there will be time for the electric and magnetic fields to collapse down on themselves before new fields are generated.

b.) If, on the other hand, the frequency is above 500,000 cycles per second, there won't be enough time for the collapse to take place before a new pair of fields is set up. In that case, the old fields will be pressured to *flip off* the antenna to make room for the newly fields. When this happens, you end up with an *electro magnetic field* that moves out in space.

c.) This is how *radio waves* are produced by radio stations.

16.) Radio waves are a form of *electromagnetic radiation.* That means:

a.) They move at the speed of light, as do all electromagnetic waves.

b.) The only difference between radio waves and light waves is:

i.) Light is generated in a different manner.

ii.) And whereas radio waves are electromagnetic waves that exist between 500,000 and 2,000,000 Hz, light waves are electromagnetic waves that exist between 7.50×10^{14} Hz (violet light) and 4.29×10^{14} Hz (red light).

17.) So why are we going through all of this? Back to the section's initial question, "If a wave is a disturbance that moves through a medium, and if light is a wave that is able to travel through the nothingness of space, what is the *medium* through which light waves travels?"

a.) Although it may not be obvious, it happens to be true that alternative magnetic fields induce electric fields, and alternative electric fields induce magnetic fields.

b.) In other words, light can travel through the nothingness of space because its electric field component feeds its magnetic field component, and vice versa.

c.) Put a little differently, light is a odd duck. It essentially *is* its own medium.

D.) Light, the Wave:

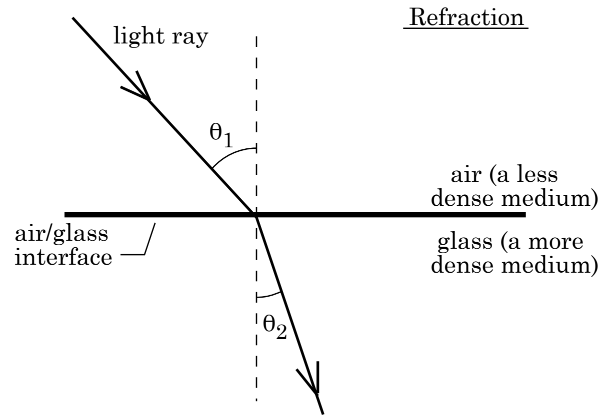
1.) There are instances when light acts like a wave. There are instances when light acts like a particle. The next several section are devoted to light acting like a wave.

2.) As a reminder, when light is treated like a wave, its defining characteristics are its wavelength and frequency. The frequency range of optical light (i.e., the kind of electromagnetic radiation your eyes are sensitive to) is 7.50×10^{14} Hz (violet light) to 4.29×10^{14} Hz (red light). The wavelength range that corresponds to these frequencies is 4000 Å (violet light) to 7000 Å (red light).

E.) Refraction:

1.) Consider a train of light waves that strike an air/glass interface at an angle θ_1 with the normal (see figure). Passing through the interface, observation shows that the light will leave at an angle θ_2 that is less than θ_1.

This phenomenon of light changing directions as it passes from one medium into another is called *refraction.*



2.) Does the speed of light vary?

a.) Experimental observation and Einstein's Theory of Relativity maintain that the *speed of light* is the same in all frames of reference. Unfortunately, if one clocks a photon of light as it passes through air, then clocks the same photon as it passes through glass, the transit times will *not* be the same. It takes light *longer* to travel through glass than air, almost as though light travels more slowly in glass than in air.

b.) The explanation of this is relatively simple. When light travels through a material, it is constantly being absorbed by the atoms of the material, only to be re-emitted a short time later. As long as the light is in motion, it moves at the speed of light--$3\text{x}10^8$ m/s. But with this constant interruption of motion through absorption, then emission, then absorption, then emission, the *effective* velocity of light through dense materials is less than $3\text{x}10^8$ m/s . . . sometimes a lot less.

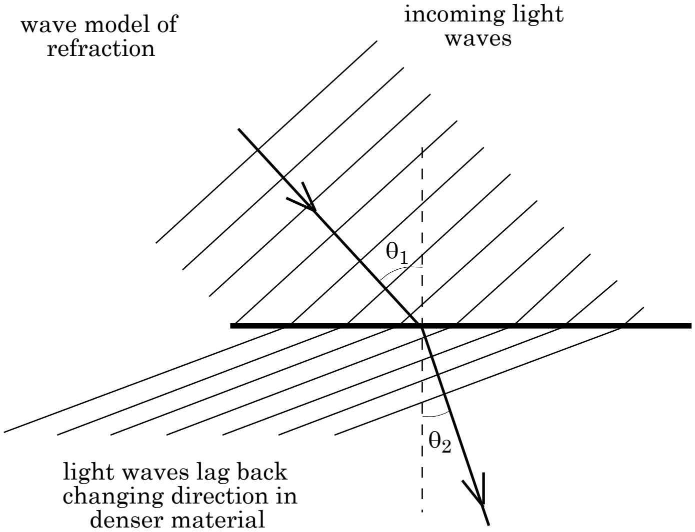
3.) Refraction explained:

a.) Each wave-front traveling in a given medium moves at the same speed over its entire wave-front.

b.) So what happens to a wave front when it passes from a *less dense* material (i.e., air in this case) into a *more dense* material (i.e., glass in this case? The figure answers the question.

c.) The *wave-front* effectively slows down as it transits into the second medium.

i.) Why? Again, because the more dense material will effect more photon *absorption then re-emission* cycles than will the less dense material, so it will take light more time to move through that material.



d.) Having slowed down, the part of the *wave front* that is in the more dense material (i.e., in the glass) does not travel as far as it would have if it had stayed in the air.

i.) This lagging back, shown in the figure, effectively changes the wave-front's direction.

ii.) By the time the entire wave has crossed the boundary, it is moving at a new angle q_2 with the normal.

4.) Mathematically:

a.) The *index of refraction* of a material, symbolized by an *n*, is defined as *c/v*, where *c* is the speed of light in a vacuum (i.e., $c = 3x10^8$ *m/s*) and *v* is the *effective* speed of light as it passes through the medium.

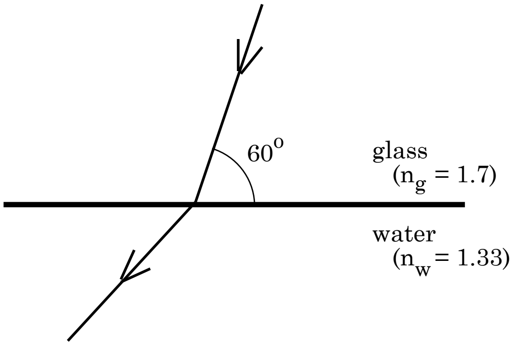
i.) In other words, $n = c/v$.

b.) Snells Law states that

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 ,$$

where n_1 is the index of refraction of medium *1*, n_2 is the index of refraction of medium, θ_1 is the angle, relative to the normal, of the incident ray (i.e., the incoming ray), and θ_2 is the angle, relative to the normal, of the refracted ray (i.e., the outgoing ray).

5.) From Snell's Law, you can see that when light passes from a *less dense* medium into a *more dense* medium (i.e., the reverse of what is shown), the ray refracts *in toward the normal.*



a.) That is, the incident angle is *greater* than the refracted angle.

b.) The opposite is true if the light passes from a *more dense* to *less dense* material (i.e., from glass to air).

c.) A pictorially clever way of showing this is

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 .$$

6.) For the amusement of it, and because you haven't really had the opportunity to work with much math so far, consider the following test-worthy example.

Light traveling in glass (index of refraction 1.7) has a wavelength of 4500 angstroms. The light passes out of the glass and into pure water ($n_w = 1.33$). The sketch shows the orientation of the incoming ray. With this information, determine: a.) the *velocity* of the light as it travels through the glass; b.) the *frequency* of the light; c.) the *wavelength* of the light once in water, and d.) *refracted angle* of the beam.

Solution:

a.) From the definition of *index of refraction*, the velocity of light in glass is:

$$\begin{aligned} v_g &= c/n_g \\ &= (3\text{x}10^8\ \text{m/s}) / (1.7) \\ &= 1.76\text{x}10^8\ \text{m/s}. \end{aligned}$$

b.) The frequency of a wave is related to its wavelength and velocity by $\nu = v/\lambda$. Using this on the glass medium, we get:

$$\begin{aligned} \nu &= v_g/\lambda_g \\ &= (1.76\text{x}10^{8}\ \text{m/s}) / (4500\text{x}10^{-10}\ \text{m}) \\ &= 3.9\text{x}10^{14}\ \text{hertz.} \end{aligned}$$

c.) Both the wavelength and velocity are variable, depending upon the medium in which they travel. What stays the same is the frequency. Knowing the frequency for the beam is $3.9\text{x}10^{14}$ hertz, the velocity of light in water, and the fact that $\lambda_w = v_w/\nu$, we can determine λ_w. Doing so yields:

$$\begin{aligned} \lambda_w &= \nu/n_w \\ &= (c/n_w) / (3.9\text{x}10^{14}\ \text{hertz}) \\ &= [(3\text{x}10^{8}\ \text{m/s})/(1.33)] / (3.9\text{x}10^{14}\ \text{hertz}) \\ &= 5.784\text{x}10^{-7}\ \text{meters, or } 5784\ \text{Å.} \end{aligned}$$

d.) As for determining the refracted angle, the first thing to notice is that the sketch is misleading. All angles used in optics are measured <u>*relative to the normal*</u>. The angles given are relative to the surface of the interface. That means the incident angle is *not* 60°, it's 30°.

Using Snell's Law:

$$\begin{aligned} n_g \quad \sin\theta_g &= n_w \quad \sin\theta_w \\ (1.7)\sin 30^{\circ} &= (1.33)\sin q_w \\ \Rightarrow \quad \theta_w &= \sin^{-1}[(1.7/1.33)\sin 30^{\circ}] \\ &= 39.7^{\circ}. \end{aligned}$$

7.) A simple example of what refraction can do for us is found in the *prism*.

a.) A prism is a piece of glass (usually) that is formed in the shape of a pyramid.

b.) When white light, which is made up of all of the wavelengths in the optical spectrum, impinges obliquely on one of the prism faces, the various wavelengths refract their characteristic amounts.

i.) Minor side point: Different wavelengths of light refract in different amounts.

ii.) Additional minor side point: Through a given interface, violet (blue) light refracts the most while red light refracts the least.

c.) If the sides of the prism were parallel, the second refraction (i.e., when the light passed from the glass back into air) would also see each wavelength refracting its characteristic amount, the net result being that all of the frequencies would recombine back into white light.

i.) A window pane, as far as you are concerned, is a very thin thing. As far as light waves are concerned, it is an enormous expanse. That is, in comparison to the wavelengths at which optical light exists, there are billions of wavelengths worth of distance between the one side of the pane and the other.

ii.) When you look through a pane of window glass and see the "right" colors coming in, it is because the two sides of the pane are parallel. How so? Any splitting up of the wavelengths of light that happens due to refraction at the first surface is undone when those same wavelengths refract at the second surface.

d.) Because the prism's faces are not parallel, each of the frequencies of light that refract at the first surface will *not* refract at the second surface in a way that will recombine all of the wavelengths back into white light. Instead, the second refraction will split the wavelengths up even more, and what you will see coming out the second side will be the individual wavelengths. Your eye translates that into different colors.

e.) Sooo, if you pass white light through a prism, you get a spectrum of colors coming out the other side.

i.) Minor side point: As violet light refracts the most, it will be the "bottom" color coming out of the prism. As red light refracts the least, it will be the "top" color.

F.) Fun With Refraction--Critical Angle, Wave Guides and Fiber Optics:

1.) There is some fairly wild stuff you can do and explain with refraction.

2.) To begin with, there is the matter of *the critical angle*.

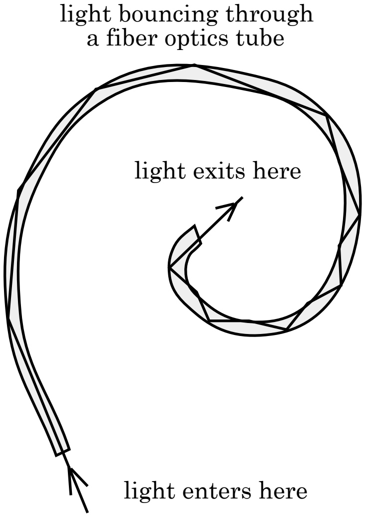
a.) When light passes from a *more dense* to *less dense* material, the ray refracts away from the normal (see figure).

b.) As such, there should be an *incident angle* at which the *refracted beam* leaves by traveling at 90^o to the normal (i.e., it leaves, moving parallel to the interface--see figure AND NOTE BELOW).

c.) The *incident angle* at which this happens is called the *critical angle* θ_c.

3.) From Snell's Law, it can be shown that the critical angle happens when $\theta_1 = sin^{-1} (n_2/n_1)$, where is the incoming *critical angle* and the n terms are the indices of refraction for the two media.

Note: In fact, whenever light strikes an interface and moves from one medium to another, a certain amount of *reflection* occurs along with refraction. As the *angle of incidence* approaches the *critical angle*, more and more light is reflected at the boundary and less and less is refracted. Once at the *critical angle*, and for all angles greater than the *critical angle*, <u>all light is reflected</u>. This reflected beam is also shown in the figure.



4.) How might his be useful? A fiber optic system can act like wave-guide for light, allowing light to travel long distances and turn corners where needed. Such a wave-guide is made up of a long, thin strand of plastic whose index of refraction n_p is very large.

5.) How does this *bouncing without loss to the outside* process work?

a.) With n_p very large and n_2 equal to 1 (I'm assuming the second medium is air), the ratio n_2/n_p becomes $1/n_p$. This is a very small number. The critical angle, $\theta_c = sin^{-1} (1/n_p)$, is therefore very small.

b.) If light strikes an interface at an angle greater than the *critical angle*, it will reflect completely, not refracting at all.

c.) An extremely small *critical angle* means that a ray has to strike the plastic/air interface almost at *right angles* to the interface (close to zero degrees, relative to the normal) before refraction occurs and light is lost.

d.) In other words, as long as the bends in a fiber optics system are not too radical, light will always strike the plastic/air interface at an angle *greater* than the *critical angle* and, hence, will always internally reflect completely (see the figure). Lossless systems obviously make ideal wave-guides.

G.) More Fun With Refraction–The Pool Experience:

1.) This next phenomenon is not directly related to the critical angle, but it does have to do with light moving from a more dense material to a less dense material.

2.) Your friend, who happens to be closely related to a South American tree sloth, has been standing absolutely motionless in your backyard pool for the last fifteen minutes. There is, in other words, not a single ripple in the pool due to the presence of your friend.

a.) You look at your friend from your lawn chair pool side. What do you see?

b.) In all likelihood, you will see your friend appearing normal from the water's surface upward, but your friend will appear scrunched up below the surface.

i.) Huh?

c.) Think about how light is acting in this case.

i.) Light enters the pool and bounces off your friend's feet (actually, the foot absorbs light, then re-emits it, but my way of stating it is close enough for now).

ii.) The light from his feet that will ultimately enter your eye, allowing you to see his feet, comes to the surface of the water/air interface (i.e., the surface of the pool) and refracts as it passes from the one medium to the other.

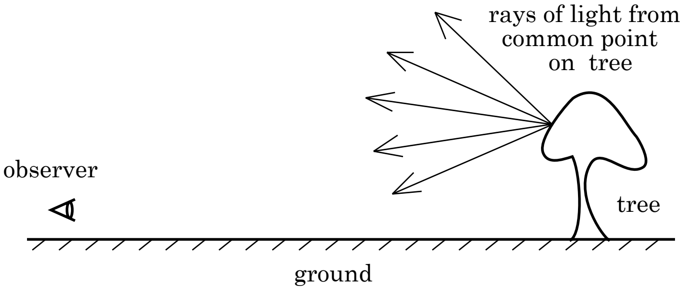
iii.) Because the light is passing from a *more dense* material to a less dense material, the angle of refraction (i.e., the outgoing angle) will be *greater* than the angle of incidence (i.e., the incoming angle). In other words, the ray we leave the water aimed lower than it normally would if the refraction phenomenon was not in effect.

iv.) "Important?" you say. Yeth thir! Because what this means is that the light you see from his feet will *appear* to be coming from a point in the water that is considerably closer to the surface than is his feet.

v.) As all the light coming from the part of his body that is below the surface will exhibit this re-direction, your view of the part of his body that is under water body will see him as being all scrunched up.

H.) Still Even More Fun With Refraction–Mirages:

1.) You are out on a flat, desert area, far away from a visible, single-tree oasis (you are the eye in the figure). Consider the rays of light coming from a point on the tree in the plane of the paper, as depicted in the sketch.

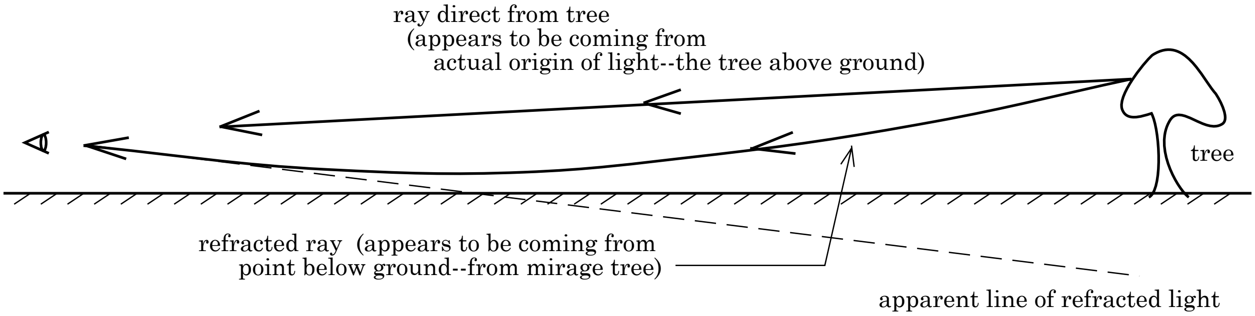


2.) At least one ray from the tree will enter your eye directly, allowing you to observe its presence. Under most circumstances, all other rays emitted in the plane of the paper will travel in straight lines and either bury themselves into the sand or go shooting off into the sky.

3.) I said, "Under most circumstances," because something odd happens when the sand is hot and the distance between the observer and tree is great. In that case, the sand heats the air just above it making the air in that region hotter than air higher up.

Heated materials tend to expand, which means the hot air near the ground has fewer atoms per unit volume with which to absorb light. In other words, the over-heated air just above the sand allows light to pass through it more quickly than is the case in the cooler air higher up.

4.) Whenever one part of a light-wave's wave-front moves faster than the rest of the wave-front, we get refraction--a changing of direction of the ray. So consider the sketch.

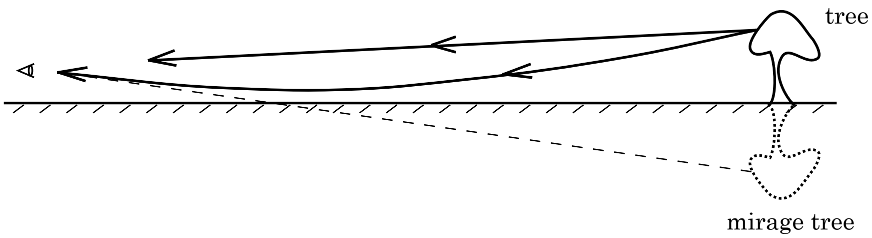


5.) The rays depicted in that sketch can be thought of as a series of wave-fronts. What is interesting is that when close to the ground, the bottoms of those wave-fronts move faster than the tops because the bottoms are in hotter, less dense air. Instead of burying themselves in the sand as would be the case if they followed a straight-line path, they refract upward.

6.) When the refracted light enters the viewer's eye, it looks as though it has come from *below the horizon-line.*

7.) Bottom line: The totality of refracted light produces what appears to the observer to be a second, inverted tree--one that seems to be sitting directly under the upright tree (see the figure).

FORMATION OF A MIRAGE from the cumulative effects of refracted light close to ground



8.) The most commonly observed kind of mirage is the appearance of water shimmering far ahead on a long, straight road on a hot day in the desert.

a.) Sky light that should bury itself into the road ahead of you is refracted a la´ the mechanism described above.

b.) This blue light, looking as though it comes from below the horizon-line, is assumed to be water.

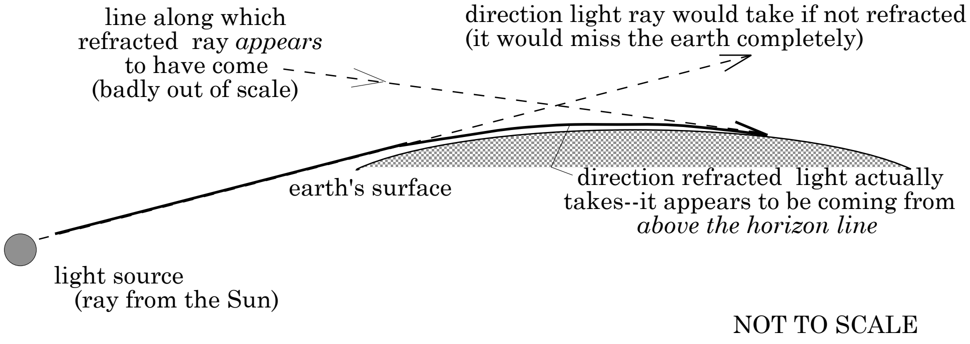
c.) The shimmer recedes because only relatively oblique rays of light traveling a long distance along the hot road are refracted enough to make it into your eyes.

9.) The second most commonly observed *mirage-like* phenomena is the sun squashing as it goes down in the evening.

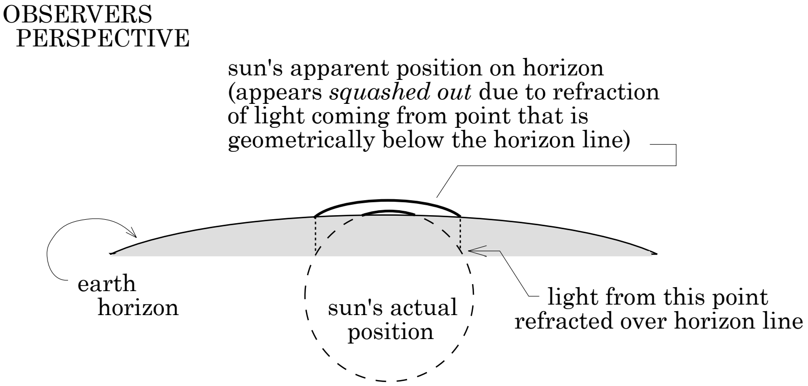
a.) Light from the sun traveling in the void of space slows down as it enters the earth's atmosphere (its effective velocity decreases). As it makes this transition, refraction occurs (see sketch).

b.) When the sun is physically almost completely below the horizon-line, most of its light should either be blocked by the earth or should go shooting off into space unseen by the observer.

c.) Light that should skim unseen through the earth's atmosphere is refracted down into your eye.



d.) Because the eye assumes light comes in straight from its source, the refracted sunlight appears to be coming from *above the horizon.* From the perspective of the observer (see sketch) this "extra sun" makes the sun appear squashed.



10.) The green flash:

a.) Why is the sky blue? Light from the sun is made up of almost all frequencies of optical light (only a few frequencies are absorbed out by the sun's atmosphere). As sunlight passes through the outer reaches of the earth's atmosphere, nitrogen compounds absorb the blue-light frequencies and re-emit them randomly.

i.) The sky is blue because blue-frequency sunlight *that would not normally hit the earth's surface* but that passes through the atmosphere gets re-directed by the absorption/re-emission process and subsequently hits the earth.

Note 1: This re-direction phenomenon is also why the sun looks red at sunset. Sunlight at sunset has to travel through more atmosphere than does sunlight at midday. The extra distance traveled allows the earth's atmosphere to absorb out almost all the blue-light frequencies leaving the predominately red-light frequencies to give the sun its sunset color.

b.) Different frequencies of light refract different amounts. Blue-light frequencies refract the most, red the least.

c.) The light you see at sunset is refracted light coming from a sun that is geometrically below the horizon (this is the most radical example possible for the situation shown in the last sketch on the previous page).

d.) The frequency of the last bit of light you see should be the frequency that refracts the most--i.e., blue light--but blue light is absorbed by the atmosphere. What you actually observe is the next most refracted light--green frequency light.

e.) If you have an unobstructed view of the horizon during sunset (looking out over the ocean is best), and if atmosphere is relatively turbulentless, the last bit of light you will see as the sun goes down will be green. This is called "the green flash."

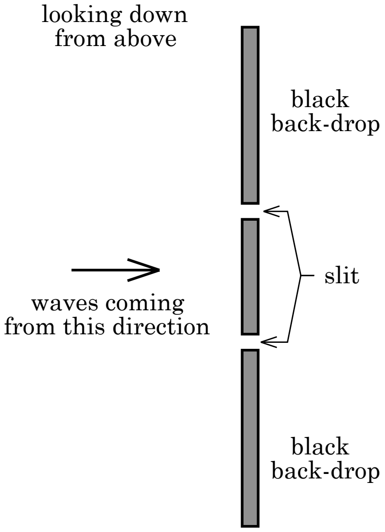
E.) The Interference of Light–Diffraction Patterns (or, the last gasp):

1.) When waves change direction as they pass from one medium into another, it is called *refraction*. When waves change direction as they pass by an obstacle (examples: sound waves going around a corner so as to be heard by someone down the corridor and away from the speaker, or water waves "go around the corner" as they pass by a jetty), it is called *diffraction*.

2.) *Light*, being a wave, can diffract. When light does so, it often superimposes with other diffracted waves creating what are called *diffraction patterns*.

3.) At the turn of the 20th century, scientists thought that light was a wave. The primary reason they believed this was due to what was called *Young's Experiment*. The experiment proceeded as follows.

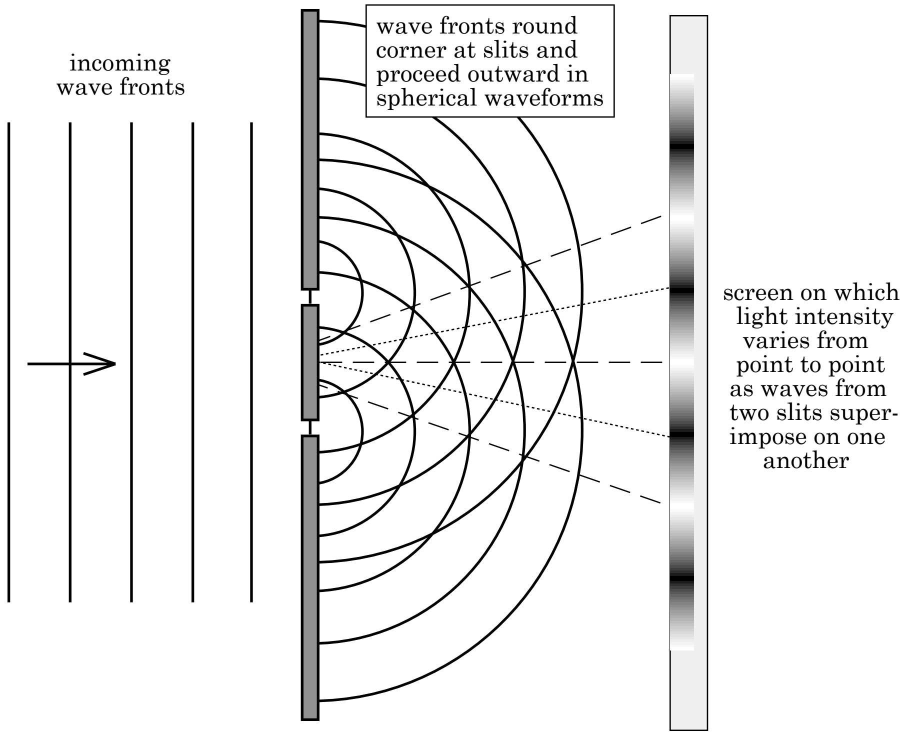
a.) Cut two thin slits in a piece of opaque material (cardboard would do). Make the slits parallel and very close to one another (i.e., a few hundredths of a centimeter apart). The figure shows the set-up.



Note: The figure is a cut-away view *looking down from above in the plane of the slits.* Toward the top of the page is shown the opaque cardboard, then a space where the first of the *slits* exists (the slit is coming up at us in this cut-away view), then the cardboard between the slits, then the second *slit*, then more cardboard.

b.) Consider *single-frequency light* from a distant source (i.e., light that comes in with its wave-fronts essentially parallel to one another).

c.) As each wave front reaches the set-up, the wave sections that strike the cardboard are absorbed. The wave sections that hit slits pass through. As each transmitted wave-front exits the slit, it "wraps around



the corners" (i.e., diffracts) creating circular wavelets on the right side of the assembly (see the figure on the next page).

d.) In effect, each slit acts like a modified *point source* of light (modified in the sense that *point sources* really produce spherical wave-fronts--the wave-fronts here are semi-circular).

e.) As the semi-circular wave fronts move outward, they superimpose on one another (again, see figure).

Note: Diffraction *always* occurs whenever light passes by a corner, but for *diffraction patterns* to be produced noticeably the *width of the slits* and the *distance between the slits* must be comparable to the size of the wavelength of the light being used. That is, light passing through an open door (approximate width: one meter) will diffract, but because the wavelength of light doing the diffracting will be somewhere on the order of 10^{-7} meters in size, a *diffraction pattern* will not be noticeable to an observer on the other side of the door. Because the wavelengths of optical light are small, only narrow slits that are very close together will produce this kind of interference.

f.) In the figure above, look at the region to the right of the slits. At every point along the DASHED lines the wavelets from the top slit superimposes *constructively* with wavelets from the bottom slit. That is, peaks superimpose on peaks and troughs superimpose on troughs.

g.) In Figure 18.8b, the DOTTED lines denote every point at which the wavelets from the top slit superimpose *destructively* with wavelets from the bottom slit. That is, peaks superimpose on troughs and troughs superimpose on peaks.

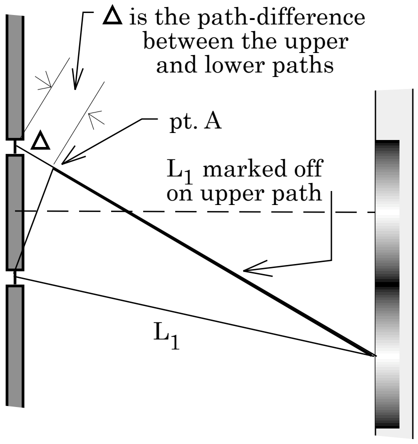
h.) If you were to place a screen to the right of the slits, what you would see on the screen would be bright fringe where the sketch's *dashed lines* hit, and dark fringes where the sketch's *dotted lines* hit.

i.) If light had been acting like a particle as it passed through the slits, there would be two bright fringes on the screen, and that would be that. That is not what the experiment shows.

j.) The bright fringe, dark fringe, bright fringe, dark fringe, etc., interference pattern is clearly a wave phenomenon. This is why scientists up until the early 1900's believed that *Young's experiment* provided the definitive word on light. Light, it was concluded, must be a wave.

4.) As an interesting side note, the key to all interference phenomena, *Young's Experiment* included, is based on what is called *path difference*.

a.) To see this, consider the figure. In it you see the slits, a central axis leading to the central bright fringe (sometimes called "the zeroeth fringe"), and a line from slit-center to the first bright fringe *out from the central fringe* (hereafter called the *first fringe*). The sketch also defines the slit separation *s*, the length *L* between the slits and the screen, and the distance y between the center of the central fringe and the center of the first fringe.



b.) In the sketch, additional information is shown: Along with the central axis, rays from both slits to the first fringe are shown, and the length of the lower ray (L_1) is laid off on the upper ray leaving a path difference between the two rays of Δ (the letter *A* has been used to denote the end-point for this measure).

c.) The question arises, "What mathematical relationship must exist if the wave-fronts that follow those two rays are to interfere constructively as they superimpose at the screen?"

The answer is intimately related to Δ.

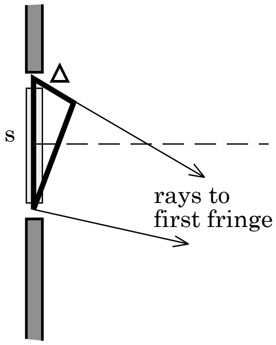
d.) For constructive interference at the screen, the wave-front located at *Point A* at a given instant must be *in-phase* with the wave passing through the lower slit. Being so, the two will travel the same distance (L_1) in the same time and will arrive in phase at the screen.

Note: If the waves at *Point A* and the bottom slit had been exactly 180^o out of phase (i.e., a trough was entering the lower slit as a crest was passing *Point A*), the two waves would have superimposed destructively at the screen and the net effect would have been a dark fringe.

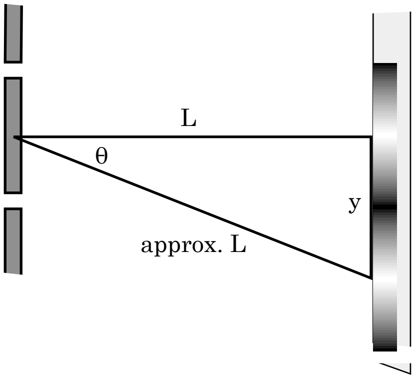
e.) Before striking the card board and the slits, the original wave-front is in phase with itself. That is, the wave-front passing through the upper slit is in-phase with the wave-front passing through the lower slit. At a given instant, the only way the wave-front located at *Point A* can be in-phase with the wave passing through the lower slit (and the upper slit as well) is if the *path difference* is equal to *one wavelength*.

Mathematically stated, that means:

$$\Delta = 1\lambda .$$



f.) Although it may not be evident in the sketches, the two triangles highlighted in sketches are similar triangles. Noting that to a good approximation the hypotenuse of the triangle in Figure 18.10b is L (L is very large while y is tiny), we can invoke the similarity of the triangles and write the ratios:



$$\Delta/s = y/L.$$

$$\Rightarrow \quad y = (\Delta/s)L$$

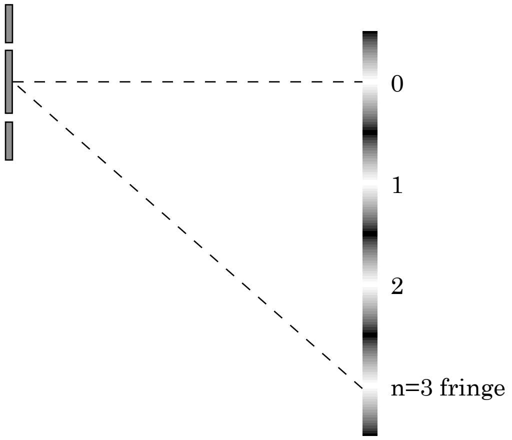
Substituting in for Δ yields:

$$y = [(1\lambda)/s]L.$$

g.) <u>Bottom Line</u>: The mathematics of situations in which diffraction occurs can be deduced by examining the *path difference Δ* between the distances traveled by the rays of light that create the interference pattern.

Note: Looking back at our original sketch, there are other bright fringes on the screen. They are produced by the superposition of rays whose *path differences* are 2λ, 3λ, 4λ, etc. Some of these are shown in the sketch to the right.

Generalizing, the *n^{th} fringe* will require a path difference of $n\lambda$, which means the most general *bright-fringe* position equation is $y = (n\lambda/s)L$. (You can now see why the central fringe--$n = 0$, $y = 0$--is sometimes called *the zeroeth fringe*.)



5.) As for the diffraction patterns themselves.

a.) A double slit set-up will produce a diffraction pattern that has a very broad central fringe, but the outer fringes will be uniform in size but considerably smaller than the central fringe.

b.) A single slit will also produce a diffraction pattern, but all of its fringes will be relatively thin and all will be the same size.

c.) It is possible to make a diffraction grating out of hundreds of parallel thin slits. The grating will create an interference pattern that is similar to the single slit pattern, but the fringes produces will be considerably more defined.

i.) In fact, many spectroscopes don't use prisms to break up incoming light into its composite colors, they use diffraction gratings.

6.) And lastly, the distance between fringes gets farther apart as the distance between double slit gets closer.

7.) And lastly, lastly, you can get similar fringe patterns through a single slit, and through a diffraction grating made up of hundreds of slits.

8.) This idea of "path difference" is the basis for the color variation seen when you look at light off of a thin film like a soap bubble or a very thin layer of oil or gasoline on water.

PHYSICS EXAM SUMMARY
2004-2005

I have said that you should know everything I talk about in class plus everything you read as a consequence of the class. This, of course, makes for a very easy summary. KNOW EVERYTHING.

Having said that, there are obviously things that are more important than others. This review sheet is meant to highlight those things. If you master all of the topics on the sheet, you will do just fine on the test. In no particular order, starting with the notes, going to the book, then going to the manual:

1.) In general, what is a wave?
2.) What is one medium through which sound waves move? Can you think of others?
3.) You are in a movie theater watching *Star Wars*. The scene has you watching a space battle while sitting out in space. The dastardly "death star" finally

blows up accompanied by the sound of a monumental explosion. At this point in the movie, you have every right to do what?
4.) How is a wavelength defined? What are its units? If I gave you a wave with some dimension to it (not necessarily a crest to crest distance, but *some* distance), could you find the wavelength from that information.
5.) What does frequency tell you? What are its units?
6.) What is the relationship between a wave's velocity and its frequency and wavelength?
7.) What is a node? An antinode?
8.) What is the difference between *constructive superposition* and *destructive superposition*?
9.) How does the Doppler Effect work? If a siren is coming toward you, is its frequency higher, lower, or the same as the siren's "natural" frequency? Draw a diagram to justify your response.
10.) What is *red shift*? What is *blue shift*?
11.) How is Doppler Effect used in Astronomy (briefly). What causes it for stellar object that are near (i.e., within our galazy) and for objects that are far?
12.) What is an *electric field*? (That is, how is it defined?)
13.) What is the unit of *charge* in the MKS system of units?
14.) What is Coulomb's Law?
15.) What produces *magnetic fields*? That is, how are they generated?
16.) What is an *electromagnetic wave*? How fast do they move? What are three examples of them?
17.) How can light as a wave travel through the emptiness of space? (be brief)
18.) What is the range of wavelength over which optical light spans? What is the range of frequencies?
19.) What is the difference between *reflection*, *refraction*, and *diffraction*.
20.) How is the *index of refraction* defined?
21.) If a beam of light passes from a *less dense* to a *more dense* medium, will it refract *toward* the normal or *away from* the normal? What about the reverse?
22.) What do you need for a mirage. That is, what causes them?
23.) What is *Snell's Law*?
24.) When using Snell's Law, angles are measured from where?
25.) Why (how) does a prism break light into its component frequencies?
26.) What is the *critical angle*? If a light ray comes in at an angle greater than the critical angle, what does it do at the interface?
27.) Be able to ray trace someone in a pool (this is the same as ray tracing what the fish sees in the manual on page 100). Ray trace to find the image of an object in a flat mirror. Find the focal point and center of a spherical mirror.
28.) Several things appear to happen when the sun goes down at sunset? What are they and why do they happen?

29.) Only one question about thin slits: if you move the slits of a double slit in closer to one another, what do the interference fringes appear to do? (This is related to the pair of concentric circles you were supposed to look at during the *diffraction* lab.)

30.) In general, why do you get very well defined colors when viewing a thin film like a soap bubble or a thin sheet of oil or gasoline on water? (You can ignore the math associated with *thin films*).