1. Physics in Music

Sound and Waves

1.1 Introduction to Sound and Waves

A yodeler in the Swiss Alps gives a loud, musical call to a far-off listener. An opera singer produces a sustained high note, causing a goblet to shatter. A piano tuner checks the piano strings with a tuning fork. The wind causes a harp to play random notes in an impromptu musical composition. All of these are examples of the marriage of physics and music. By studying the former, we can better understand and produce the latter.

We shall begin with sound. Sound results when a vibrating object puts the surrounding molecules into motion. Although it is certainly possible to produce sound underwater or in a solid object, we will deal primarily with the production of sound and music in air. Thus, the molecules that are put into motion are air molecules.

The speed at which the sound waves travel determines how long it will be before the sound is heard by a listener. As the disturbance is not a single moving object but rather a series of collisions between molecules, there is no acceleration, and the equation describing the forward motion of the sound wave reduces to the following:

$$v = \Delta x \,/\, \Delta t$$

where, you will recall, v = velocity, Δx = change in position, and Δt = change in time.

Sound moves through any particular medium with a speed dependent upon the properties of that material. It moves quickly through materials which are dense, such as steel, and more slowly through media which are sparse, such as air.

Even the temperature of the medium affects the speed of the wave. Thus, sound travels more quickly through warm air, where the molecules that pass along the waves are already moving quickly. Sound travels more slowly through cold air, where the molecules pass along disturbances more sluggishly.

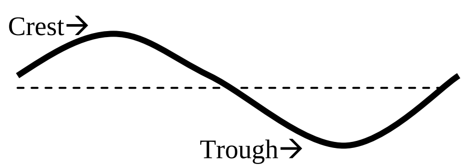
The exact speed of sound in air can be calculated with this formula:

$$v = 331.5 \text{ m/s} + 0.6*(T)$$

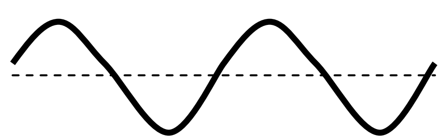
where v is the velocity of the sound in m/s and T is the temperature of the air in degrees Celsius.

Our yodeler can determine how far it is across the canyon by timing how long it takes his echo to return and by consulting his thermometer to find out the temperature of the air for his calculation of the speed of sound. A dolphin in the ocean instinctively uses his cries and squeals of echolocation in the same manner to determine how far away objects are from him.

But this only explains how fast the sound moves, not which notes will be heard. Consider a single sound wave. It will have a crest, where the molecules are squeezed together, and a trough, where the molecules have been pulled apart. You can picture this wave as a snakelike sine wave, although the air molecules are truly moving together and apart rather than up and down.



Now imagine putting two sound waves into the same space.



For two waves to fit in, the **wavelength** (symbolized by the Greek letter lambda: λ), or horizontal size of the wave, had to be reduced to half its original size. A listener would hear sound waves twice as frequently as in the previous case. This new wave has a higher **frequency** (f) and a smaller wavelength than the original wave. The higher frequency wave sounds to the listener like a higher pitched note. Thus **pitch** is simply the frequency of the sound wave.

The **period** of a wave (T) is the time it takes for one complete wave to pass an observer. It's similar to wavelength, only for time instead of length!

One final detail: if the listener is hearing *twice* as many waves as before, each wave must take only *half* as much time to be completed as before. Thus frequency of the wave (f) is inversely proportional to the time for one wave, or period (T). In other words, $f = {}^{1}/T$.

To assimilate all of this information into equation form:

Recall that $v = \Delta x / \Delta t$.

In this example, the change in position is one wavelength ($\Delta x = \lambda$), and the change in time is the period for one wave ($\Delta t = T$).

$$v = \lambda / T$$

And since $f = {}^{1}/T$, this reduces to:

$$\boxed{v = f \lambda}$$

which is known as the "Wave Equation."

1.2 Natural Frequency

An object made from a pure substance will, when struck, vibrate at a specific rate known as its **natural frequency**. The natural frequency of an object is dependent upon its physical dimensions as well as the materials it is made of. Thus a set of wooden wind chimes and a set of aluminum wind chimes will give off distinctly different notes even if they are made to the same specifications, and two sets of aluminum wind chimes made to different dimensions will also give off different musical notes.

The concept of natural frequency helps to explain why a guitarist's "fingering" affects the notes sounded; by changing the string length, he is also changing the natural frequency of the string. A violinist also uses this principle when she presses the string to the fingerboard to alter the note played by the bow. A musician who tightens or loosens the tension in the strings of his instrument is tuning it by altering the natural frequencies of the strings until they are pleasing to the ear.

Strike a tuning fork and touch it to a table, and the table will start to vibrate at the same rate as the fork, creating a much louder sound than the fork could alone. Yet the table and fork have very different natural frequencies. This is an example of **forced vibration**. Objects touched by a vibrating object will vibrate at that frequency even if they have fundamentally different natural frequencies. This forced vibration is the basis behind the sounding board and the reason behind the sizes and shapes of instrument bodies. The larger surface areas of the sounding board and instrument body allow them to push greater volumes of air than strings alone could. This in turn makes the sound waves stronger and thus louder to the listener.

1.3 Warming up instruments

Have you ever noticed how before a concert the musicians will play random practice pieces and pause often to tune their instruments? One would think that they would come to the concert with their instruments already prepared; why, then, do they always have this warm-up session?

Before musicians can be confident that their instruments will produce the proper frequencies of sounds, they must have the instruments and the air contained within them warmed up to the temperatures they will have during the concert. In wind instruments, pitch is directly related to the speed of sound in air. As a wind instrument begins to warm up, its pitch for a given finger position will actually increase. Thus what began as **B** may upon warming up become "**B**-sharp." In stringed instruments, pitch is dependent upon the tension of strings, which decreases as the strings become warmer, lowering the pitch and making the intended **B** note into a "**B**-flat." Since there is no way to eliminate the heat from friction of playing, a musician must warm his or her instrument to be certain it is tuned properly for the concert.

1.4 Sympathetic Vibration and Overtones

A sitar is a lute-like instrument from India which is noted for possessing two sets of strings, only one of which is plucked by the musician. The second set of strings vibrates without contact, seemingly by magic. It is a perfect example of **sympathetic vibration**.

When you sympathize with someone, you feel the same way he or she feels. Similarly, sympathetic vibration is when one object begins to vibrate when another object of the same natural frequency vibrates nearby. What seems like magic becomes easily explained when you think of pushing a child on a swing. If you push at just the right intervals, the swing will go higher and higher without requiring much effort on your part. If you push at the wrong times, you may even bring the swing to a complete halt. In the same way, when a vibrating object shakes the air around it, the air then buffets anything else it hits with the same frequency.

Most objects are like the second swing, where the waves do not help create more movement but tend to damp it out instead. If the second object has the same natural frequency as the first, though, it will respond like the first swing, which gets greater and greater movement over time. This is sympathetic vibration. It is a valuable tool in music, adding a mellow richness to the tones created by an instrument. In addition, our piano tuner above will use sympathetic vibration to tune his instrument. When a tuning fork of a particular pitch is struck, the proper string will begin to vibrate sympathetically if it is in tune.

With stringed instruments, the lower the tone played, the richer it seems to sound. Is this simply a quirk of our brains? In truth, this richness is caused by **overtones**, which are simply strings which are an octave or more higher than the note played which also vibrate. To understand this, consider the child on a swing again. The swing will go quite high if you push each time in synch, but it will still rise fairly high if you push every other time instead. Thus strings which are multiples of the fundamental frequency played will also vibrate sympathetically, though much softer than the original note played. The lower the note, the more strings there are which can have sympathetic vibration, and thus the richer the resulting tone.

1.5 Beats

Informally, if you've "got the beat", it means you move in time with the rhythm of the music. In physics, it takes on a quite different meaning. Strike two xylophone pipes of the same frequency, and you will hear one loud sound. However, strike two pipes of slightly different frequency and the sound will oscillate, getting louder and then softer in a smoothly rolling manner. This variation of the loudness of sound is called **beats**.

Recall that sound waves are made when air molecules are pushed together and then pulled apart. When two objects vibrate at the same frequency, crests of both sound waves overlap, as do the troughs, making a stronger, louder wave. When the objects have different frequencies, though, the crests will periodically occur in synch, making a louder sound, and periodically occur out of synch, making a softer sound. This is the origin of the oscillation in loudness, the tremolo effect of music known in as beats. To determine how many beats will occur between two vibrating objects, use the following equation:

$$\#\ \text{beats} = f_2 - f_1$$

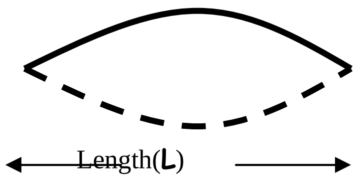
where f_2 and f_1 are the frequencies of the vibrating objects.

Our friendly piano tuner can make good use of beats if striking a tuning fork doesn't induce the sympathetic vibration in the proper string. He or she can then pluck the string and strike the fork, listening to the beats produced and tightening or loosening the string as needed to make the beats reduce in number until they eventually disappear entirely.

1.6 Fundamental Frequencies #1: stringed instruments

If you pluck a guitar string, the waves which can be sustained are constrained by the two ends of the string, which must remain fixed. Such fixed points are called **nodes**. Positions of maximum movement, such as crests and troughs, are called **antinodes**. The longest wave which can fit on the string without being damped out is exactly half the length of the string; because it is the lowest frequency wave allowed, it is called the

fundamental frequency. As you watch the string vibrate, the wave and its reflection will form a pattern that seems not to be moving at all, earning its name of **standing wave**. It is important to remember that standing waves only appear not to move; in fact, the waves and their reflections are constantly in motion.



$\lambda = 2L$ f_1 (fundamental frequency) (first harmonic)

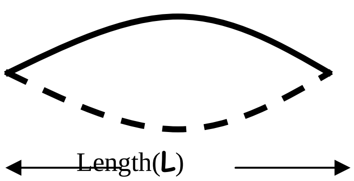
The fundamental frequency for a particular string can be calculated by combining the above information with the wave equation as follows:

$$v = f\lambda \quad \text{and} \quad \lambda = 2L$$
$$v = f_1\,(2L)$$
$$f_1 = v\,/\,(2L)$$

Waves of other lengths can also form standing waves within the same vibrating string. These waves are called **harmonics** and will all be of higher frequency and shorter wavelength than the fundamental frequency wave. The second harmonic has a node in the center of the string, while the third harmonic has nodes placed at the 1/3 and 2/3 mark along the string.

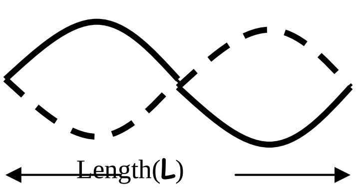
Fundamental Frequency (first harmonic)

$\lambda = 2L$ frequency = f_1



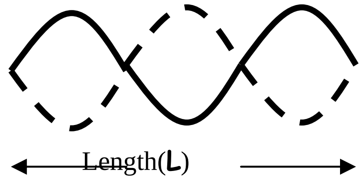
Second Harmonic

$\lambda = L$ frequency = $f_2 = 2f_1$



Third Harmonic

$\lambda = 2L/3$ frequency = $f_3 = 3f_1$



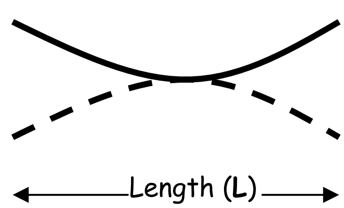
Notice that each successive harmonic is an integer multiple of the fundamental harmonic. This can be summarized as the following general equation:

$$f_n = nv/\,(2L)$$
where $n = 1, 2, 3, \ldots$

When the string of a guitar is plucked, you hear not only the fundamental frequency, but also higher harmonics. Thus even a sound which appears to be a single pitch is a combination of many frequencies. In music, it is the mixture of harmonics which causes the property of timbre, which the listener identifies as sound quality.

1.7 Fundamental Frequencies #2: open pipe instruments

An example of an open pipe instrument would be a piccolo. In this case, instead of both ends being clamped, as is the case with the stringed instruments, the ends are open, allowing molecules a complete range of motion. Instead of nodes at the ends, there are crests or troughs, which are collectively known as antinodes. The picture below demonstrates why the fundamental frequency for open pipe instruments is identical to that of stringed instruments: the smallest wave to fit inside still has a wavelength of twice the length of the instrument.

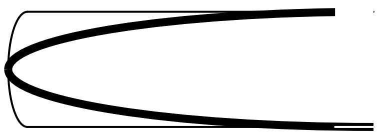


It should also be clear after a moment's thought that the equations for calculating harmonics for an open pipe instrument are the same as those for stringed instruments.

1.8 Fundamental Frequencies #3: closed pipe instruments

A closed pipe instrument refers to an instrument which is open at one end but sealed at the other. A seashell fits this description, with its roaring ocean sounds originating from background noise, some waves of which are the exact length required to create standing waves within the spiral shell.

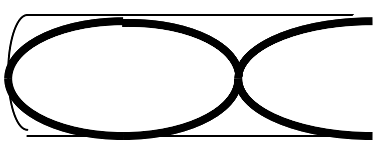
One more typical instrument to fall in this category is the closed pipe organ, but reed instruments such as the clarinet also fit, since they have an open end and a fixed end. This means that the waves which will fit must each have a node at one end, where the air molecules cannot move, and an antinode at the other end, where the air molecules have maximum motion. The smallest wave to fit this pattern is one whose length is four times the length of the pipe.



Therefore, the fundamental frequency for a closed pipe instrument is as follows:

$$f_1 = v / \lambda = v / (4L)$$

The next harmonic must occur when ¾ of the wave fits into the pipe, as this is the next case when one end of the pipe has a node and the other has an antinode. This means $\frac{3}{4}\lambda = L$ or $\lambda = {}^4/_3 L$



$f_3 = v/({}^4/_3 L) = 3[v/(4L)]$ or $f_3 = 3f_1$

Notice that for instruments with one closed and one open end, the harmonics occur at even intervals from the fundamental harmonic, varying by the odd integers. This can be generalized as:

$$f_n = nv/(4L) \quad \text{where } n = 1,3,5,\ldots$$

Any instrument which has a reed at one end, such as a clarinet, will behave like a closed pipe instrument. However, it must be understood that the above derivation presumes a cylindrical instrument body; in reality, very few instruments will follow this ideal case perfectly. This is why instruments have such varying sounds.

1.9 Scales in Western Music

The western musical scale uses the value of the standard A_4 (440hz) to determine 6 other notes: B_4, C_5# ("C_5 sharp"), D_5, E_5, F_5#, and G_5#. The value of each note can be calculated using the value of A_4 and the following ratios in order: 9/8, 5/4, 4/3, 3/2, 5/3, and 15/8. By multiplying the frequency of A by the proper ratio, the other notes can easily be determined. There are actually 5 additional notes used in western music, giving a total of 12 notes and 11 intervals between them that compose the scale. The five other notes are: B_4^b ("B_4-flat"), C_5, D_5#, F_5, and G_5. Also, the pitches of all notes except A_4 are adjusted slightly to be more pleasing to the ear. Thus the values you calculate will be close to but not exactly equal to those of your musical instrument.

To determine the value of a note an octave higher, double the original frequency; to determine the value of a note an octave lower, halve the original frequency. Thus A_5, an octave higher than A_4, has a frequency of 880hz, whereas A_3 has a frequency of 220hz.

Problems to do:

1. It is 10°C outside the morning Johan yodels across to his friend Sven who lives on the next mountain. What was the velocity of sound?

2. If Johan heard his own echo 3.5 seconds later, how far apart are the two mountains?

3. How long after Johan yodeled would it be before Sven would hear it?

4. If the temperature were 25°C, how much **sooner** would Sven hear the call than originally?

5. When lightning occurs, the sudden heating of the air causes it to expand abruptly,

sending a shock wave through the air known as thunder. Thunder, therefore, moves at the speed of sound. In air which is 25°C, how fast does thunder move?

6. One mile is approximately 1610 meters. For the same 25°C day, how long does it take thunder to travel one mile? Round your answer to the nearest second.

7. Light travels so quickly that lightning is seen almost the same moment it is created. Use this and details from above to explain why people count "Mississippi One, Mississippi Two,…." when they see the flash, stopping the count only when they hear the thunder.

8. Scales used in western music are centered around the note A_4, which has been set at 440hz. What is the period of this note?

9. Assuming that sound travels at 343 m/s through the air, what is the wavelength (λ) of an A_4 note?

10. A_5 has twice the frequency of A_4, whereas A_3 has half the frequency of A_4. What are their respective frequencies?

11. What are the wavelengths of A_5 and A_3 notes? (Assume that sound travels at 343 m/s through the air)

12. If each octave is exactly half the frequency of the previous octave, what must the frequencies of A_2 and A_1 be?

13. Presuming an average speed of sound of 343 m/s, calculate the wavelengths of the notes from A_1 through A_8.

14. A bass singer creates notes from 80hz to 300hz. What wavelengths of sound can he produce? (Assume that sound travels at 343 m/s through the air)

15. A soprano's range of notes lies between 300hz and 1100hz. What wavelengths can she produce?

16. Can you make someone hear your music sooner if you sing higher than normal? Explain why or why not.

17. What physical differences are there between low and high pitched notes sung by an opera singer?

18. Calculate the first three harmonics for a harp string of length .20 meters.

19. Calculate the first three harmonics for a xylophone pipe of length .20 meters.

20. Calculate the first three harmonics for a closed type organ pipe of length .20 meters.

21. Calculate the frequencies of the 7 notes that form the octave centered about A_4.

22. Determine the theoretical values for the 7 notes an octave lower than the previous problem. Recall all notes are relative to the A!

23. Which property of physics does the musical instrument the triangle use?

24. Why don't all pipes of a xylophone produce the same notes?

25. Would it make a difference if a xylophone pipe had one end sealed? Explain.

26. Why don't equivalent notes in different types of instruments sound alike?

27. If two xylophone pipes, the 440hz and the 442hz, are sounded together, how many beats will be heard each second?

28. If you have a 220hz xylophone pipe, what two other pipes could be used to make 5 beats be heard?

2. Physics in Music

Sound Interactions

2.1 Reflection

Just as light can bounce off a mirror, so can sound waves reflect off of various surfaces. Such sound reflections are called **echoes**. If it strikes a soft, irregular surface, the echo will be weak, as most of the energy of the sound is absorbed into the material or reflected in various directions. If the material encountered is hard and smooth, the echo will be strong, as most of the energy is returned in a single direction.

Rooms which have many excellent reflecting surfaces may experience **reverberations**, which are multiple echoes. This is what happens when a band attempts to give a concert at the local gymnasium. The reverberations may be strong enough to mask the original music.

Reverberation time refers to how long echoes audibly persist after the original sound is made. Because human speech consists of many short, rapidly occurring syllables, a long reverberation time may mean that subsequent words are garbled or masked by the echoes. Reverberation times of a half second or less are preferred. On the other hand, rooms with short reverberation times make music sound flat and "dead." Opera houses may benefit from as much as a 2.5 second reverberation time. The length of the reverberation time can be altered by the materials within the room; softer materials tend to shorten the time, while more rigid materials lengthen it.

All reflection of sound may be undesirable in places such as a recording studio, when each sound introduced to the room is carefully choreographed for pitch, duration, and timbre. In such cases, walls may be padded with cork or other materials to absorb the sound energy rather than reflecting it back.

2.2 Refraction and Diffraction

You have probably noticed how a pencil stuck in a glass of water seems to be bent. You may not realize, however, that sound can exhibit that same bending. As waves of any sort move from one medium into another, part of the wave begins moving at a new speed while the rest of the wave is still moving at the old speed. This results in the bending of the wave known as **refraction**. During the day, when the ground has heated up and the air above is cooler, the yodeler's call will tend to be refracted upwards. This is because the sound travels faster near the warm ground and overtakes the slower sound in the cool air, causing the entire wave to be directed slightly upwards

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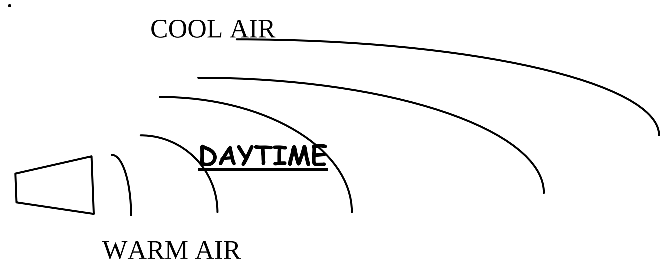
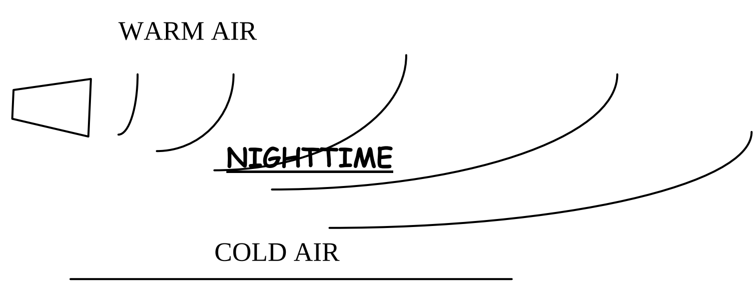


The opposite effect will occur at night, when the quickly-chilled ground causes the sound to refract downwards, allowing you to hear the party going on at the cabin across the lake from you.



In addition to the changes made by sound entering a new medium, sound can also bend around corners in a property called **diffraction**. Unlike solid objects, which move in straight lines unless forces act on them, waves act to fill in all empty spaces. This is why you still hear the music even when you are around the corner from the room it originates in.

2.3 Interference

Because sound is a wave, it has the ability to temporarily combine with other sound waves to create a new wave with a quite different shape and/or amplitude (loudness). This wave interaction is called **interference**. As the waves continue past one another, their separate wave properties once more become evident, neither having been permanently changed by the interaction. Two waves which make a stronger wave are showing **constructive interference**, while two waves which serve to damp each other demonstrate **destructive interference**. Both types of interference are useful in music.

Constructive interference occurs when two or more waves combine such that their crests tend to add together and their troughs add together. This exaggeration in maximums causes the resulting sounds to be louder and may cause a more complex note to be heard as well. Constructive interference is used by amplifiers and microphones to increase the loudness of a sound.

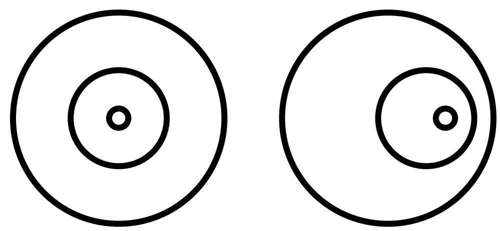
The opera singer whose sustained pure note causes a crystal goblet to shatter is using the ultimate constructive interference. By buffeting the goblet with waves at its natural frequency, she causes it to vibrate harder and harder until it shakes itself apart. This act of forcing an object to vibrate repeatedly at its natural frequency is called **resonance**.

The opposite effect of destructive interference is also useful in music. We tend to think of music as the sounds which are produced; it is also a product of the interspersed silences. However, sometimes destructive interference occurs when it is unplanned. This is the case with "dead spots" in concert halls, where the original sound waves and their reflections meet crest-to-trough, resulting in a significantly softer sound wave. A solution might be to make concert hall walls oddly shaped so there will be reflections in many directions. The more waves which are added together, the less likely they are to completely cancel one another out.

2.4 The Doppler Effect

If you've ever heard a train's whistle change pitch as the train passed by, you've witnessed the **Doppler Effect**. To understand the origin of this oddity, imagine the following scenario. You are listening to Bruce Willis play the saxophone on a steamy summer night. Each note he plays causes the air to vibrate with that same frequency, transferring the sound energy across the night air until it buffets your ear and your brain recognizes the sensation as music.

If he always plays the same note, you receive vibrations at regular intervals, and thus hear a constant sound. However, if he is playing while in a moving car, when the car moves away from you the vibrations of the air will not reach you as often as they should. If you receive waves less frequently (that is, at a lower frequency), you will hear a lower pitch than is being played. If the musician is moving towards you, the waves will be crimped together so that you receive them more often than you should, making them sound higher pitched than the original notes. This change in frequency due to relative motion of musical source and listener is the Doppler Effect.



No Doppler Effect **Doppler Effect**

Be aware that this is *not* the change in amplitude (loudness) which will occur as the source of music comes closer or moves away; it is the change in frequency of the music you hear. Also, you will only hear a *rising* pitch if the musician is accelerating towards you so that the frequency with which you receive waves is *constantly increasing*, you will only hear a *dropping* pitch if the musician is accelerating away from you so that the frequency of the waves is *constantly decreasing*.

2.5 Sound Intensity

Anyone who has attended a rock concert and snagged a front row seat knows that the **intensity** of the music heard is dependent upon your location as well as the music being produced. When an instrument creates sound, the energy is transferred from the instrument to the surrounding air in a wave that propagates in all directions. The rate at which that energy is transferred through a given area is called the sound intensity.

Picture the sound wave as a balloon which is being inflated. There is a finite amount of balloon material which is being stretched over a greater and greater surface area as the balloon expands. Similarly, as the sound wave expands in a spherical shape about the source, the energy is spread over a greater and greater area. Thus the farther the listener is from the musical source, the more spread out that energy has become, and the less intense the resulting sound. Intensity (**I**) is simply the rate of transfer of sound **energy** ($\Delta E/\Delta t$) or **power** emitted (**P**) through a spherical surface of radius **r**. That is:

$$\text{Intensity} = \frac{\Delta E/\Delta t}{\text{area}} = \frac{P}{\text{area}} = \frac{P}{4\pi r^2}$$

Since power has units of watts and area has units of meters^2, intensity has units of W/m^2. Although there is some variation, a typical person has the ability to hear a sound intensity as small as 1.0×10^{-12} W/m^2 and can tolerate an intensity as large as 1.0 W/m^2. Sounds below the former level are below the threshold of hearing , while those above the latter level are above the threshold of pain and can cause damage to the ear. It is important to realize that damage can occur even when the listener experiences no physical pain. For this reason, musicians and listeners exposed to high intensities of music should wear special headphones, earplugs, or other protective devices designed for this purpose.

Whether a particular sound is audible is dependent upon both its frequency and its intensity. Sounds requiring the least intensity to be heard are those frequencies located in the middle of our hearing range. It is there that the frequencies used most commonly in speech are located. Musical frequencies range slightly above and below our speech range, and nonmusical sound ranges beyond that.

2.6 Relative Intensity: Decibels

Although loudness is related to intensity, it is not directly proportional. Instead, the human ear operates on a logarithmic scale. Thus when intensity increases by a power of ten, a listener hears the sound as twice as loud as before, and when the intensity increases by a power of one hundred, the listener hears the sound as four times as loud as the original sound. With each power of ten the intensity increases, the loudness is doubled.

Relative intensity, measured in decibels (dB) relates intensity to the range of human hearing. Zero decibels marks the threshold of human hearing; though it does not mean there is no sound, a listener would just barely be able to detect *something*. Zero decibels is approximately 1.0×10^{-12} W/m^2. Ten decibels is about as loud as rustling leaves. The softest whisper might be around 20dB, which is heard as twice as loud as the 10dB leaves. A jet plane taking off, producing a relative intensity of around 130dB, would be 2^{11} times louder than that whisper.

2.7 Detection of Sound: the Human Ear

The human ear serves the function of converting the kinetic (motion) energy of the vibrating air molecules into electrical energy of the nerve impulses detected by the brain. In its way, this is similar to a microphone. The process begins with a sound wave which enters the ear, causing the tympanum, a thin membrane commonly called the ear drum, to begin to vibrate. Three tiny bones in the middle ear transfer these vibrations to a watery liquid, which in turn transmits the waves to the tiny hairs of the spiral shaped cochlea. Sound waves of different frequencies cause different regions of the cochlea to resonate, stimulating particular hairs which in turn stimulate nerve endings that send impulses to the brain. The brain then recognizes a sound of a particular frequency and loudness.

2.8 Problems to Do:

1. How are reverberations different from echoes?

2. What causes a room to have excellent reverberations?

3. Where are some locations where having reverberations would be a good thing?

4. Where are some locations where having reverberations would be detrimental?

5. Why do automated phone systems often sound so robotic?

6. Why do short reverberation times often result in inferior music?

7. What can be done to reduce reverberations?

8. What is refraction?

9. When will sound refract downwards? Why?

10. When will sound refract upwards? Why?

11. What allows you to hear music even when you are around the corner form the source?

12. What property allows waves to combine temporarily with other waves?

13. Explain what must be true about two waves for them to constructively interfere.

14. How could two musical notes cause silence?

15. What are "dead spots" in theatres, and how can you get rid of them?

16. When the pitch of a passing ambulance changes, what physics concept have you just experienced?

17. How can you tell if the approaching train is moving at constant speed or accelerating as it blows its horn?

18. Why do you hear a change in pitch as a moving object passes by you?

19. Do you hear a change in pitch as a musician approaches you while playing B flat on a flute? Explain why or why not.

20. You are standing 3.0 meters away from a set of amplifiers at a concert. You can barely tolerate the intensity of the sound emerging. What power was being emitted from the amps?

21. This time you are sitting 1.0 meters away from your best friend, who is listening to a CD on a headset. You can just barely catch a snatch of the music that he is listening to if you concentrate. What was the power emitted through the headset to the rest of the room?

22. What two properties determine whether a particular sound is audible?

23. Why might some people be able to hear music but be deaf to human speech?

24. How is loudness related to intensity?

25. If the loudness of the music is doubled, by how much did the intensity change?

26. If you quadruple the loudness of the music, by how much did the intensity change?

27. If you decreased the intensity by ten times, how would the loudness change?

28. If you increased the intensity by 100 times, how would the loudness change?

29. What does zero decibels represent?

30. What is the approximate intensity of zero decibels?

31. If you increase the noise level in a room by 20 decibels, what happened to the loudness?

32. If you increased the noise level in a room by 30 decibels, what happened to the loudness?

33. How is energy changed by the ear and brain to make sound?

34. Explain how the inner components of the human ear allow you to hear.

35. How does the ear register different frequencies of sound?

3. Physics in the Arts

Light – a bright subject ☺

3.1 Types of Light

Curtains and blinds reduce the amount of light allowed into a room. Lamps extend the length of the natural day. A flashlight brightens a dark basement. Emergency flashing lights alert other drivers to the presence of a stalled car in the road ahead. Each of these examples demonstrates a typical use for light.

However, "light" (the common term for electromagnetic radiation) includes not only the light we see, but also frequencies which are too high or too low for our eyes to register, including: radio waves, microwaves, infrared waves, ultraviolet light, x-rays, and gamma rays.

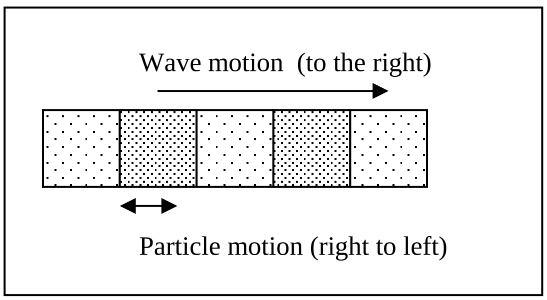
Type of Light	Range (approximate only)	Uses
Radio Waves	$\lambda > 30cm$ $f < 1.0 \times 10^9 hz$	AM and FM radio, television, cell phones
Micro-waves	$30cm > \lambda > 1mm$ $1.0 \times 10^9 hz < f < 3.0 \times 10^{11} hz$	Microwave ovens, radar, aircraft navigation
Infrared Waves	$1mm > \lambda > 700nm$ $3.0 \times 10^9 hz < f < 4.3 \times 10^{14} hz$	Infrared photography, night vision binoculars, physical therapy
Visible Light	$700nm(red) > \lambda > 400nm(blue)$ $4.3 \times 10^{14} hz < f < 7.3 \times 10^{14} hz$	Visible light photography, microscopes, telescopes
Ultraviolet Light	$400nm > \lambda > 60nm$ $7.5 \times 10^{14} hz < f < 5.0 \times 10^{15} hz$	Sterilization of medical instruments, identification of fluorescent minerals
X-rays	$60nm > \lambda > 10^{-4} nm$ $5.0 \times 10^{15} hz < f < 3.0 \times 10^{21} hz$	X-ray photographs of bones, cancer treatments, etc
Gamma Rays	$.1nm > \lambda > 10^{-5} nm$ $3.0 \times 10^{18} hz < f < 3.0 \times 10^{22} hz$	Cancer treatments, food irradiation, examination of thick materials for structural flaws

We don't all see objects the same. If our eyes were set up to see "radio light" then we would see a radio station shining like a beacon. Some animals can see heat (infrared) as a color.

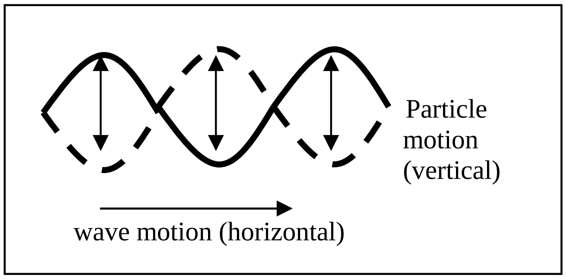
3.2 Some Properties of Light

Depending on the situation, light will act sometimes as a particle and sometimes as a wave. We will be dealing almost exclusively with its wave nature, examining traits such as interference and reflection which we have discussed before in connection with sound waves.

Light, unlike sound, does not require a medium, as witnessed by the fact that while sound cannot travel through the vacuum of space, light can and does. Our best evidence for that is the fact that we receive light from the sun. This peculiarity means that light is fundamentally a different type of wave than sound. Sound forms a pressure wave, pushing air molecules together and apart as it propagates. This type of wave is called **longitudinal**. In a longitudinal wave, the particles move back and forth in the same direction the wave moves.



Light waves, on the other hand, follow a sinusoidal path, moving in a snakelike s-shaped pattern as they propagate. Such a wave is called **transverse**. Imagine shaking a jump-rope; the particles move up and down while the wave moves forward and back down the rope. This is how you can picture a light wave.



3.3 Colors of Light

Most people are familiar with the colors produced by a triangular glass prism when it is placed in sunlight: red, orange, yellow, green, blue, and violet. The reason for the dispersion into color will be discussed later; for now it is most important to realize that the white light that entered the prism was made up of all those colors. The glass merely allowed the colors to be seen separately.

The color a sample of light has is dependent upon the frequency or frequencies of light which are present. Each broad color category has its own frequency range, and mixing colors allows the eyes to experience a myriad of variations.

All frequencies of light move at the same speed, however, and this value is constant for light traveling through a vacuum such as space. This value, given the representative letter **c**, is approximately 3.00×10^8 m/s. To three significant digits, this value is the same for light traveling through air. The wave equation, as applied to light, is as follows:

$$c = f\lambda$$

3.4 Objects in Color

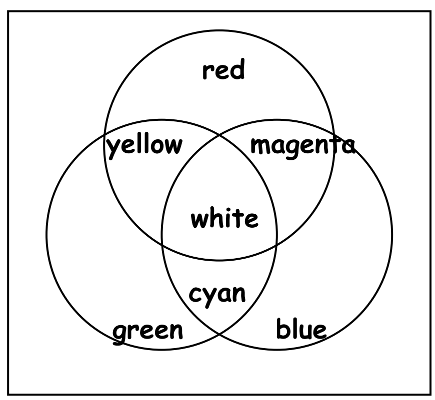
You are able to see an opaque object when light from that object is reflected to your eye. Thus a blue shirt is blue because the material reflects blue to your eye and absorbs other colors.

If you recall the last time you visited a museum or cathedral, you probably at some point during the trip viewed a stained glass window. Stained glass windows, and other light filters, are different from opaque objects in that you view the light which the filter transmits while other colors are absorbed by the material. A blue stained glass window is blue because it allows blue light to go through while absorbing all other colors. This is true of all transparent materials.

3.5 Theatre lighting

In a theatre, there is not enough physical room or, generally speaking, the money available to have spotlights in every color which might be needed in a play. Fortunately, the lighting crew may make use of the primary mixing colors of light and use only three colors of spotlights with which to create many, many effects.

The three primary mixing colors for lights are red, green, and blue. With different amounts of those three colors, all colors of light can be created. When all three primary colors of light are blended, the resulting light is white, whereas when there is an absence of color, the result is black. This is different from mixing paints and pigments, which will be discussed later. The color mixing circles below show the results of mixing the three primary colors of light.



By consulting the color mixing circles, you will quickly see how the red and blue spotlights, used together, provide magenta light on stage, the blue and green together show cyan (a blue-green color), and the red and green spotlights when simultaneously used give a yellow light. A little further thought will show that varying the intensities of the three primary colors will give additional colors. For example, when the red and green lights are on and the red lights are significantly stronger than the green, an orange colored light will shine on stage.

3.6 Costumes on Stage

Under white light, a yellow shirt appears yellow because it reflects red and green light while absorbing blue light. A green tie looks green because it reflects green light and absorbs red and blue. However, when the same objects are viewed under different colored lighting, their colors alter.

What if the stage lights were blue? The erstwhile yellow shirt now has no green or red light to reflect, and it cannot reflect blue; therefore, it absorbs all the light which strikes it, reflecting nothing at all. If it reflects nothing, it appears black. The green tie, also having no colors it can reflect, appears black as well.

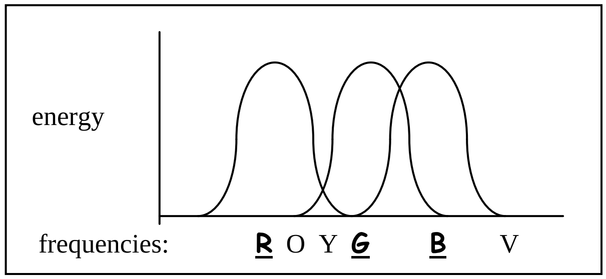
What if the lights were red? Here, the shirt can reflect the red light, appearing red, but the tie absorbs all of the light that strikes it, appearing black. Notice that the lighting used in combination with various costume colors made it appear as though costumes had altered colors.

3.7 The Human Eye and Seeing Color

The retina of the eye, contains two types of receptors which detect the presence of light: rods and cones. Rods are located on the periphery of the retina and mainly detect low intensities of light. When you are stargazing and notice out of the corner of your eye a star which disappears when you look at it head-on, you have made use of the rods. They cannot detect color with any precision.

The second type of receptor, the one which fills most of the retina and can detect color, is the cone. There are three kinds of cones: red, green, and blue. It is not a coincidence that these are the same three colors as form the basis of the color mixing circles for light; on the contrary, this is the reason that those particular colors have the ability to create all wavelengths of visible light.

Each cone registers its own color the best, but can also weakly detect some frequencies on each side in the electromagnetic spectrum. Therefore, although the green cones detect green light best, they will also detect some frequencies of yellow and blue light. The light energy each cone can detect forms a bell curve, such as shown below.



This graph shows the ability the three cones have for detecting different frequencies of light. One interesting quirk about human color vision is that we may see a particular color, such as violet, because that is the frequency of light being sent to our eyes, or because that is the particular color our brain registers when it combines the information from all three types of cones. We cannot visually distinguish between these two colors.

3.8 Color Deficiency

When a type of cone is missing in a person's eye, their abilities to register that color of light are drastically reduced. This is the case of **color deficiency**. (Because in most cases people *do* see color, simply a reduced range, the term "color blind" is no longer used.) Approximately forty five percent of the cones in a typical person's retinas are red cones, forty five percent are green cones, and the remaining ten percent are blue cones. Ironically, the rarest cones, the blue ones, are also the least likely to be missing; red and green cone color deficiency are far more common.

3.9 What the Color Deficient See

When someone is missing one of the three types of cones, the variety of colors they perceive is greatly reduced. For example, if a person is missing the red cones, she will not only have difficulties detecting reds, but also will see distortions of yellows and purples, both of which are made

A person suffering from **monochromacy** is truly color blind. He cannot distinguish any wave-length from any other wavelength. What he sees is similar to what a xerox machine prints when you copy a color photograph. These people may see patterns which others do not, and they often cannot distinguish patterns which other people easily see. Monochromacy results from either a lack of two of the three types of cones, or a lack of all cones with an accompanying reliance on the rods for all visual information.

Next time you are outside at night, try to identify the colors of houses and cars in an unfamiliar and dimly lit neighborhood. Because the cones cannot register under those conditions, the rods, which do function under low light conditions, will be providing all visual information. Since they do not register color, you will see basically varying shades of gray. This is much like what a monochromatic person sees all the time.

A person who shows **dichromacy** is missing one of the three types of color cones. If you refer back to the energy/frequency graph on the previous page, you will notice that there are areas where the curves of two cones overlap. This means both cones register those frequencies somewhat. Thus even if one type of cone is entirely missing, that individual may be able to detect –though only dimly-- some colors normally registered by the missing cone. However, any frequencies which are not in an overlapping zone would not be registered by the remaining two cones and thus would be seen as black.

A dichromatic individual is apt to adjust his television set so that the frequencies which are hardest for him to see send out stronger than usual signals. In this manner he can more easily see those colors. To a chromatically unimpaired person, that would result in a picture whose colors in some hue are unpleasantly overblown.

3.10 Afterimages

Occasionally the viewer seeing the "wrong" colors is the artist's intent. For example, special **afterimage** paintings are deliberately done in the "wrong" colors; the true artwork is seen on a blank white screen after the viewer stares at the painting. But what are these afterimages, and what causes them?

Stare at a purple object for 30 seconds and then gaze at a plain white wall, and you will see an image of the same object, except in green. Try the experiment with a blue object, and the image you will see will appear yellow. In each case you have experienced afterimages, an effect of the human eye.

When you look at an object for a long time, the cones which have been registering those colors become tired of firing. A fatigued cone will not respond as strongly as normal. Your red and blue cones got fatigued when you stared at the purple object, so when you looked at the white wall, which should make all cones fire equally, they only responded weakly. The green cones fired normally, making the image seem more strongly green than red or blue. In the case of the blue object, the blue cones tired out and fired more weakly than usual, but the red and green cones fired normally, creating a strongly yellow image.

Determining the colors necessary to produce particular afterimage effects is simple when you consult the color mixing circles. Two colors which add to make white are called **complementary colors**.

Thus red and cyan are complementary, as are magenta (or purple) and green. In each case, the afterimage color is the complement of the original light.

3.11 Color Constancy

The three cone theory of color vision explains many of our daily experiences and allows us to predict with fair accuracy the results of numerous situations. However, there are some peculiarities which this traditional model does not explain which have led scientists to propose the theory that the brain is also directly involved in the perception of color.

Take a look at the colors of the clothing you are wearing as you sit indoors and then observe them again after walking outside. If the traditional view were correct, the different lighting conditions of the two locations should cause your clothing to send to your eye slightly different relative amounts of red, green, and blue should change as you move outdoors, and they do not. The fact that they remain approximately the same under varied lighting conditions is a result of **color constancy.**

The brain does not rely on the information given to it by the cones alone. Instead, it uses the colors of an object's surroundings to help determine the color of that object

3.12 Filming with Blue Screens

If you could go behind the scenes of the new **Star Wars** movie, you might be disappointed. Not because George Lucas has run out of cool ideas or plot lines (he may have, but that's a separate issue!). What would be most disappointing is the fact that the actors do most of the filming in front of a blue screen and the background is added later.

In other words, while the actors are cringing in terror from some monstrosity, the casual observer would see nothing but blue. Bummer.

The way this works is a combination of light and computer imaging. The blue background is a certain color (frequency) of light. The computer scanning the film detects which parts of the film that contain that frequency and which parts do not. The computer can then combine the background patterns with the actors, superimposing the background on top of the blue frequency parts only. Thus, the actors can appear to stand in front of any scene imaginable

Television announcers often use this technology as part of their shows. Sports reporters are often shown with a stadium background instead of a studio. Weather forecasters are often shown with a weather map in the background, but are actually filmed against a blue wall. Thus when a home viewer sees a meteorologist on the Weather Channel pointing to Texas as he talks about conditions there, he is actually pointing to a blank wall and using camera monitors to adjust his movements.

Once, a weather forecaster wearing a blue sweater had to quickly change clothes because her upper body seemed to disappear, giving the illusion of her head "floating" across the screen.

light. But this means the colors of your clothes

For some reason, this seemed to traumatize viewers.

3.13 Problems to Do:

1. If our radio station is sending radio waves out into the air in all directions, why don't we hear the music when standing just outside the building?

2. Our station's frequency is 88.5 mega (million) hertz. How long are the waves our station sends out?

3. Are ultra-violet light waves longer or shorter than violet light waves?

4. AM radio stations are measured in kilohertz (1000s of hertz). Are the wavelengths of AM stations longer or shorter than those of FM stations?

5. Our sun is a yellow star, which means most of the energy it gives off is in the yellow region of the electromagnetic spectrum. It appears as though the human race evolved to make best use of yellow light, as it is in the middle of our color vision range. What would our color vision range have been like if we had had a red star instead?

6. Bees have the ability to see ultraviolet light. Which colors of our color vision spectrum are bees least apt to be able to see?

7. Why are red lights used in photographic darkrooms?

8. Compare a transverse wave to a longitudinal wave.

9. Is light transverse or longitudinal?

10. How fast can blue light move in a vacuum?

11. What makes a red book appear red?

12. What makes a green stained glass window appear green?

13. What are the three primary mixing colors for light?

14. What are the three secondary colors which are produced when two primary lights are mixed?

15. What makes a yellow stained glass window yellow? (careful!)

16. How can you make a blue costume appear black on stage?

17. What color will a cyan costume appear under blue light?

18. What color will a cyan costume appear under red light?

19. What color will a red costume appear under magenta light?

20. What are the two types of receptors found in the retina of the eye?

21. Which type of receptor is used for low light levels?

22. What are the three kinds of cone receptors?

23. Explain two reasons a person's brain might register an object as being yellow.

24. What is monochromacy?

25. How does a monochromatic person see the world?

26. What is dichromacy?

27. If a dichromatic person is missing the green cones, does that mean he cannot see any frequencies normally registered by green cones?

28. What are afterimages?

29. How can you determine when particular colors will be seen as afterimage colors?

30. What are complementary colors?

31. What color is formed when all three primary colors of light are mixed?

32. For the previous question, what afterimage color would be seen after staring at that light?

33. What is color constancy?

34. How do we know the brain is involved in how we see colors?

4. Physics in the Arts

Paints and Pigments

4.1 Paints

When you add lights together, the color gets closer and closer to white light, which is a combination of all colors.

However, anyone who has ever played with finger paints knows that as you add more and more colors of paint, the result is a darker color that approaches brown or black. Thus paints and pigments must act fundamentally differently than light. Paints do not supply their own light; they rely on an outside source to provide the light that they reflect back to viewers.

Also, anyone who has played with paints knows that the primary colors are different from the primary colors for light.

	Primary Colors
light	Red, Green, Blue
pigment	Cyan, Yellow, Magenta

The reason for this aberration has to do with how pigments produce the colors we see. Let us examine a typical house paint to understand this.

Most house paints have in them both dye molecules and small, colorless particles of titanium dioxide (or a similar substance). A house paint which does not have the titanium dioxide will tend to look dull, since though the dye molecules absorb out unwanted colors, they reflect the desired color of the paint randomly, in all directions. On the other hand, a paint which does not have the dye particles will look white, as the titanium dioxide provides new materials for the light to enter, causing numerous reflections at boundaries.

Because paints are based on absorbing out unwanted colors, mixing two paints reduces the frequencies of light which will be reflected to the eye. This is called **color subtraction**. If each new paint mixed in results in more frequencies absorbed and fewer reflected, the ultimate result must be a paint which absorbs all colors and reflects none. That is, the end result is black.

(In a perverse way, one could argue that the actual color of blue paint is “not-blue” since only not-blue colors are absorbed by the paint.)

4.2 Pigments

Pigments are the powdered materials that, when suspended in a liquid, create paint. Some colors found in nature simply cannot be reproduced by artificial means. These are most often made from a rare mineral which is difficult to obtain and hard to prepare. If you wander into an art store, you will discover that some artist’s oils are extremely inexpensive, and some are so dear that a fraction of an ounce has an outrageous cost. These are the paints made from rare materials which cannot be mimicked in the laboratory.

Examples of paint colors which require rare natural pigments abound. Cobalt blue and Aureolin Yellow, neither of which can be reproduced truly by artificial means, are made from cobalt compounds. Carmine, a scarlet red paint, is made by pulverizing the exoskeletons of a particular species of insect. It, also, is rare. Emerald green is made from a copper and arsenic compound, and its like cannot be made artificially. Ultramarine, a blue paint much prized by artists from time immemorial, requires the mineral lapis lazuli to create its distinctive blue color. And there are numerous other examples.

4.3 Impressionists

It is believed that the term Impressionist came from the title of one of Claude Monet’s paintings, “Impressions: Sunrise.” The impressionists used dots and dabs of primary paint colors and white to simulate the reflection of light in their work. The original impressionists believed that color should be pure as it is placed onto the canvas rather than mixed on a palette, although this ideal became corrupted eventually. Unlike the pointillists, they allowed brushstrokes to flow against one another.

The impressionists were apt to paint the same scene again and again, under varying lighting conditions, in their attempt to paint the true objects. In a discovery of how light changes during a single day, these artists painted with amazing rapidity. They raced against the sun in their determination to achieve the desired effect on canvas before the lighting changed. They were among the first artists to successfully depict various natural lightings in their works.

4.4 Partitive Mixing and Resolution: the Pointillists

The Pointillists believed that the eye could perceive colors much more luminous than the palette could ever mix. They believed that color mixing should occur in the eye, not on the canvas. To achieve this, pointillist artists placed small discrete dots of different paint colors next to one another, never allowing them to overlap. In this manner they differed from other impressionist painters, who used dabs of paint but allowed the edges to be in contact.

When viewed from close up, paintings done in the pointillist manner would have no discernable content, but when seen from afar, the viewer's eyes melded the colors. This is the effect made famous by the Frenchman Georges Seurat in his paintings. "La Poseuse en Profil," "A Sunday Afternoon on the Island of La Grande Jatte," "The Side Show," and "Une Baignade" are just a few of the dozens of works created by Seurat in his revolutionary style.

How ever it came about, and how ever the theory was altered, it remains a fact that the impressionist style of art makes use of a concept of physics: resolution. Resolving power is the ability of the eye to produce separate images from sources which are close together. It depends on several factors, including the wave length of the light and the closeness of the two sources. For a wave length λ and a circular lens or aperture (such as the pupil of the eye) size D, the resolution angle Θ in degrees is:

$$\Theta = 70\ \lambda / D$$

If the two objects are seen at an angle bigger than Θ, they are distinguished as two separate objects; if they are closer than Θ, they are seen as a single object. The smaller the resolution angle, the greater the resolving power.

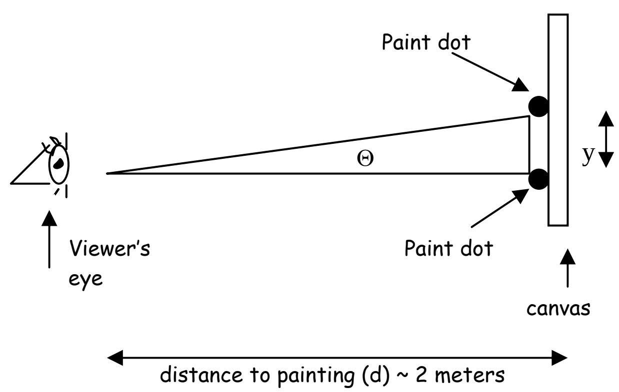
This foray into physics is all well and good, but what did it mean to the pointillists? It meant that for their paintings to be viewed as a merging of dots into splashes of color rather than as discrete dots, the artists had to paint extremely tiny dots.

4.5 Resolution of the pupil

To investigate this, let us use the typical size of a pupil, which is about 4×10^{-3}m (4mm), and a color of light in the middle of our visible light spectrum, yellow, which has a wavelength of around 6×10^{-8}m. Solving for the angle….

$\Theta = 70\ \lambda / D$
$\Theta = 70\ (6 \times 10^{-8}\text{m}) / (4 \times 10^{-3}\text{m})$
$\Theta =$ **.001 degrees**

This is much less than a single degree. What does that mean to the artist? Consider the viewer and two dots of paint as forming a right triangle as shown below.



Thus, $\tan \Theta = y / d$
Or $\tan(.001 \text{ degrees}) = y / 2 \text{ meters}$

A bit of algebra shows that $y = 3.7 \times 10^{-5}$m. This is equal to .037mm. The artists would forced to make dots less than a millimeter apart to achieve perfect results. Because this was next to impossible, Seurat and the other pointillists created paintings intended to be viewed from far distances, some so enormous they took up to a year to complete.

4.6 More examples: Fabrics and Television

A color television screen is not so different from pointillist art. It makes use of the same ideas.

Phosphors that light up red, green, or blue are spread throughout the screen. When a beam of electrons causes some of these phosphors to light up, the eye of the viewer mixes them like theatre lights, creating new patterns and colors.

Your eye is very willing to create new colors when the warp and weft (the two directions of woven threads) in fabrics are made in different colors. Quite often this is done to silk, which is fluid enough to allow the visual mixing to occur. Silk which has been made in this manner is called "shot silk." As you ripple shot silk, you will notice two strikingly different color effects, such as purple and green, which form color patches as the fabric pools in particular ways. One famous shot silk color is "Eau de Nil," which is supposed to mimic the waters of the Nile River in Egypt at its most beautiful.

4.7 Physics in the Comics Page

Next time you are reading the Sunday comics, look at the bottom of the page, and you may notice several colored boxes: some light blue, some pinkish, and some yellow. These are samples showing the three colors of ink plates used to create the color pictures. Actually, there is generally a fourth plate as well: black. The black plate, though not vital (as mixing the three inks should give a passable black), increases the contrast of the intended black regions of the picture.

Although at first glance the plate colors resemble the three colors in the simplest crayola box (red, blue, and yellow) in fact, they are not these colors at all. They are truly magenta, cyan, and yellow, the three secondary mixing colors of light. The magenta ink absorbs green light and reflects back to the eye the blue and red wavelengths. Similarly, the other inks absorb some colors and reflect others.

4.8 3-D Glasses

A number of years ago, 3-D movies and photos were all the rage. Viewers would don cardboard glasses with red and blue lenses in them and then watch a special screen. They would experience a peculiarly three-dimensional effect, as though people and objects in the scene were reaching out towards them. This is an effect caused by both pigments and lights. The screen image was truly a composite of two images, one made in red and one made in blue (or occasionally green). These two images would be slightly different from one another.

The eye viewing through the blue lens would be unable to distinguish between the white screen and the blue images on the screen; they would both be reflecting blue light which could pass through that lens. Like white and blue costumes seen under a blue light on stage, they would appear alike, and so the blue images would disappear from that eye's view. The red images, though, would be clearly seen, as no red light would be allowed through the blue lens. Thus the red image on screen would look black.

The other eye, with its red filter, would be unable to see the red images that are projected on screen, but could clearly see the blue images as black regions where light would not be allowed through the lens. If the two images projected, the blue and the red, are different perspectives of the same scene, then each eye is getting a slightly different picture. This is the basis behind stereo vision. Objects look like they have depth when we see them from two slightly different perspectives at the same time.

4.9 Computers and Virtual Painting

One of the challenges facing a computer programmer designing a virtual art easel is how to mimic the mixing of paints using the lights of a computer screen. Mix blue and yellow light, and the result is a white light. Mix blue and yellow paint, and you get green. Thus the programmer must write the codes so when the artist smears blue and yellow on screen, the computer shows the original blue and yellow regions correctly as well as an acceptable green color where they overlap. Real paints blend subtly, creating many intermediate colors as mixing occurs; the computer codes must be written so the art on screen shows this delicate blending as well.

4.10 Fluorescence

If something fluoresces, it glows while under ultra-violet lighting. The mineral calcite changes from a whitish color under natural lighting to an orange-red under ultra-violet light. It **fluoresces**. It is this concept which is used in art to make black light Elvis posters. The pigments in the posters absorb ultra-violet light, which our eyes cannot see, and re-emits it as visible light. These lights are particularly common in haunted houses and other places where dark is desired.

Fabric brighteners and whiteners used on your laundry use fluorescence as well. They add a substance to your wash which absorbs ultraviolet light which is naturally given off by the sun and by man-made lights, and re-emits that light in the visible range. Now not only does your clothing reflect the visible light that you're used to seeing, but it also fluoresces, adding to the intensity of the light reaching your eyes. Your whites appear whiter and your colors brighter. (This is starting to sound like a commercial! ☺)

One of the newer fads is bleaching teeth to improve whiteness. The process here is similar to that of the laundry detergent, but the exact chemicals used are different. Some toothpaste companies put whiteners into the product, but white teeth in magazine ads are a totally different effect because the teeth are often air-brushed to appear whiter than they are in reality.

4.11 Phosphorescence

Some materials due to their chemical makeup will continue to glow for a while after the ultra-violet light is removed. These objects are said to **phosphoresce**.

Many watches have phosphorescent dials on them so they can be read in the dark. Glow-in-the-dark marbles and similar toys work on the same principle. They only glow again after they are "recharged" by the exposure to more ultra-violet light.

4.12 Sun-Fading

As humans, we tend to ignore what we cannot see. This means we often pay little attention to wavelengths of light which are unable to be seen by our eyes. We have already discussed the role of ultra-violet light in fluorescence and phosphorescence. There is another area where non-visible light is important to the arts, and that is **sun-fading**.

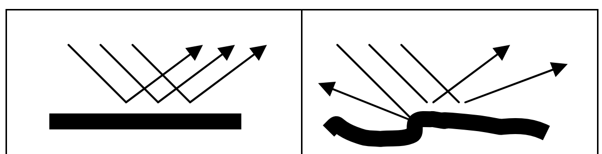
The last time you or a friend repainted a room, you probably discovered that there were squares of darker colored paint on the walls under prints and paintings that had been hung in the same spot for a long time. You can get the same effect in a shorter time span by placing some small objects on a piece of construction paper and leaving the paper where the sun will shine on it. In a matter of weeks, there will be a distinct difference between the color of the paper under the objects and the exposed paper. The lightening of the exposed paper is caused by sun-fading.

Sun-fading is actually a form of radiation damage, but nothing that should have you running for a radiation suit. Photons of ultra-violet light striking the object in question bump off electrons that help to bond dye molecules together. The dye molecules fall apart, leaving the paper without color.

4.13 Reflective Surfaces

Anyone who has gotten involved in home remodeling has at some point discovered the myriad of paint finishes available for covering walls. Gloss, semi-gloss, and matte are only a couple of the available finish types available.

Recall the discussion on echoes and reverberations in the physics and sound unit. Light has a similar ability to reflect as sound. It can either reflect as a unit or randomly.



a smooth surface reflects together	a rough surface reflects randomly

A matte finish results when the paint's slightly rough surface causes the light to reflect in various directions. In physics this is called **diffuse reflection**; it is similar to reverberations in sound. The viewer will only get a small portion of the light reflecting back to him, so the colors will not seem particularly bright.

A glossy finish results when the paint's more polished surface reflects the light all in the same direction, much like the creation of a single echo in sound studies. Because a larger percentage of the light is being reflected to the viewer, he will see stronger colors than with the matte finish paint. This is sometimes called **specular reflection**.

Other paint finishes are created by varying the nature of the surface in a manner similar to the two given examples.

4.14 Problems to Do:

1. a) What are the three primary mixing colors for light?
   b) What are the three primary mixing colors for paints and pigments?

2. When you mix two paints, does the mixture reflect more new colors, or absorb out more new colors than the original paint?

3. What is the purpose of the dye particles in a paint?

4. What is the purpose of the titanium dioxide particles in the paint?

5. What is color subtraction?

6. What are pigments?

7. Why are some paint colors more expensive than others?

8. Why did Impressionists paint the same scenes repeatedly?

9. What techniques did Impressionists use to create their effects?

10. Explain partitive mixing.

11. What is resolving power?

12. How did pointillists make use of resolving power?

13. Will a telescope which has a smaller resolving power be able to resolve more or fewer stars?

14. Why would visible light telescopes have small lenses while radio telescopes (telescopes that receive radio waves from space) must have huge dishlike antennas?

15. What is the resolving power of our eye for red light?

16. Should it be easier for us to distinguish two red stars which are close together or two blue stars which are close together?

17. How is the tv screen like a pointillist painting?

18. How does woven silk use color mixing?

19. What are the three colors of ink plates used in the Sunday comics in the paper?

20. What problems arise from designing computer programs for artists?

21. Why must you have two different lens colors when you create 3-D glasses?

22. What would be the effect of using glasses with yellow and red lenses?

23. What is the role of perspective involved in 3-D pictures?

24. How could you create a 3-D movie using this idea?

25. What makes an object fluoresce?

26. Name a mineral which fluoresces.

27. How would you know if something were fluorescent or if it were phosphorescent?

28. Why do objects fade in the sun?

29. Explain the difference between specular and diffuse reflection.

30. When you get a glare from the headlights of an oncoming car off a rain-slicked road, which type of reflection are you experiencing?

31. When you look at yourself in a mirror, which type of reflection are you seeing?

32. What causes paints to have different finishes?

33. How are paints and lights fundamentally different?

34. What would a pointillist do to create a yellow tint to a region?

35. Referring to question 34, why would such a yellow never be as pure as a yellow spotlight shown on a white canvas?

5. Physics in the Arts

Reflections on Light

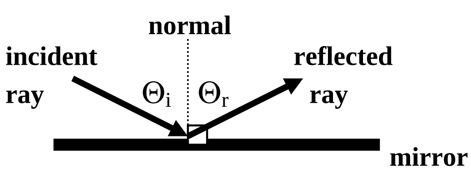
5.1 flat mirrors

Throughout the ages, mirrors have been highly prized for their ability to produce an accurate likeness of a person or scene. Whether used in amusement park activities, artwork, or as dental tools, mirrors are all fundamentally alike. They are all highly polished materials that make use of the law of reflection.

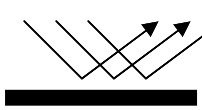
The **law of reflection** states that the angle at which a ray of light strikes a mirror is the same as the angle it reflects at. In physics terms, we say the **incident** (in-coming) **angle** is equal to the **reflected** (out-going) **angle**.

$$\Theta_i = \Theta_r$$

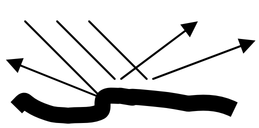
Both angles are measured from a line which is perpendicular to the surface that the light ray strikes. This line is called the **normal.**



Recall the earlier discussion on diffuse and specular reflection. The law of reflection works for all materials, but when the surface's normals change, the reflected rays do not come off parallel to one another; this results in diffuse (matte finish) reflection.



Specular surface (glossy finish)

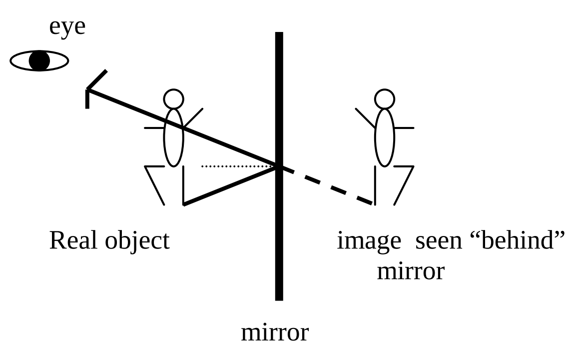


diffuse surface (matte finish)

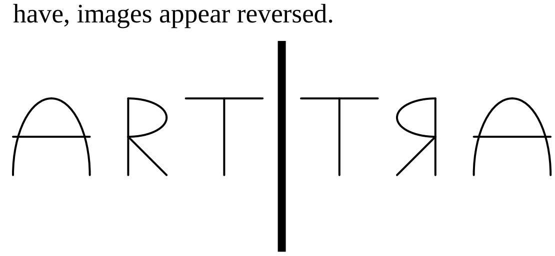
If you've ever tilted a paper to see if the white-out has dried, you have used these ideas. When it is liquid, the white-out shines specularly. When it dries, it is rougher, becoming a diffuse reflector.

The smoother the surface, the stronger the resulting reflection of light. Most materials absorb some light and reflect the rest; this means most objects will only provide a weak reflection. The brain can easily tell the difference between a weak reflection and the real object.

However, mirrors reflect nearly all light incident upon them. The eye, unaware that the light it detects been detoured, sees a strong image *behind* the mirror. That is, when you look at yourself in the bathroom mirror, you see your image as existing behind the mirror, though you know that to be an impossibility. Your *brain* tells you it is an image and not a real object located there.



The image you see in a flat mirror appears to be as far behind the mirror as the object is in front of the mirror. In addition, the image is exactly the same size as the original object. There are differences between the original object and its image, though. Because images have the same distance to the mirror as the original objects have, images appear reversed.



mirror

Because an image formed from a flat mirror can never be focused onto paper, it is called a **virtual image**. A virtual image is one which can be seen only when looking into a mirror or through a lens. Just like virtual reality games in which you see objects which you cannot actually touch, virtual images are ones which you can see but not touch or focus onto a screen.

5.2 Kaleidoscopes and Mirror Houses

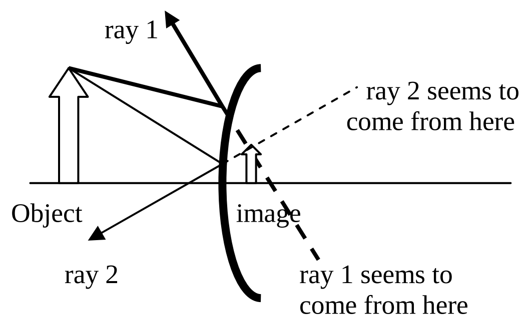
The more perfect the mirror, the harder it is for the eye to detect that the light's path has been altered. A house of mirrors at an amusement park is an excellent example of this. The walls of the house are all mirrors polished so that it is difficult to tell images from original objects. Because you see multiple reflections as you move through the house, you are apt to reach for a doorknob only to find your knuckles bumping into the solid glass of a mirror. Dim lighting can assist this impression, as it makes both objects and images dimmer and thus harder to distinguish from one another.

Kaleidoscopes also make use of multiple flat mirrors. A kaleidoscope is a long, cylindrical device with two plane mirrors running the length of the tube and a hole at one end in which to look. The unusual geometric designs seen in a kaleidoscope are actually multiple reflections of colorful objects placed inside the kaleidoscope. When the angle between the mirrors is an integral factor of 360 degrees (such as 45, 60, or 30 degrees), the viewer will see complete and distinct virtual images in a symmetric pattern. Other angles will show reflections as well, but the images will overlap, and thus the images and original objects will be easily distinguished from one another.

5.3 Curved Mirrors: convex

In the corner of a typical shop you will see a large mirror shaped like the back of a spoon. If you look into it, you will see images of nearly everything in the store. Because such a large scene is shown in such a small amount of space, all of the images are much tinier and they seem farther away from the mirror than the original objects. No matter where you view the mirror from, you will always see small, upright, virtual images. This anti-theft device is a **convex** (outwardly curving) mirror.

A similar mirror is used for the side-view mirror on the passenger's side of a car. Such mirrors can be very useful, as they show a greater range of view than a flat mirror would. However, because the images are not the same size as the original object, and because they do not appear the same distance "behind" the mirror as the original object is in front of it, the driver might mistake the distance of approaching cars. For this reason, the message "objects in mirror are closer than they appear" is etched on the glass.



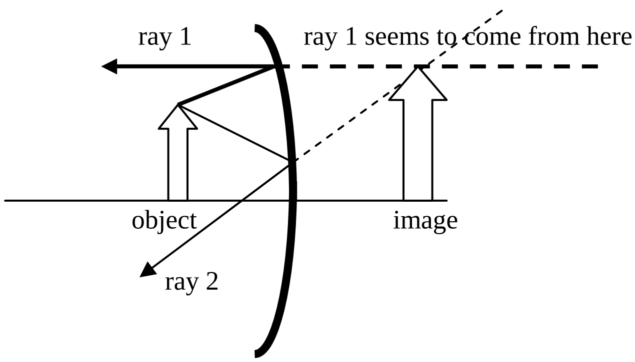
all images produced by a convex mirror are small, upright, and virtual

Notice that the light rays are actually diverging as they leave the mirror. This is what makes the image a virtual one. The viewer thinks the rays originated from a spot behind the mirror because that is the direction the light is coming from. Since the rays never truly crossed, they can never be focused onto a screen. These images exist only in the eyes and minds of the viewers. However, if the viewer happens to be a camera with film, the camera will "see" what the eye sees, and the film will be exposed in the pattern of the virtual image. This is not the same as having the image form directly on a screen.

5.4 Curved Mirrors: concave

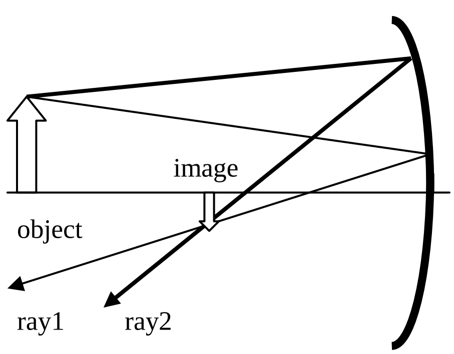
On the top of many a vanity counter is a mirror which is curved inward, like the inside of a spoon. If you look into this shaving or makeup mirror, you will see an enlarged, upright, virtual view of your face. This is a **concave** mirror.

Place a concave mirror on a counter in front of you so that you can see your face reflected back at you. You should see an image larger than life.



objects close to a concave mirror produce large, virtual, upright images

Now back away from the mirror slowly. At a certain point, the image "whites" out; that is, you can no longer see any recognizable image at all. If you continue to back up, the image that appears is suddenly upside down. Even more bizarrely, if you hold a sheet of paper the same distance away from the mirror that you were standing when the image whited out, and aim the mirror out the window, you will see an image of what's outside projected upside down onto the paper. An image which can be focused on a screen is called a **real** image.



Objects far from concave mirrors have small, upside down, real images

In all virtual images, the light rays are diverging; that is, they are moving apart from one another. The eye is fooled into thinking the rays have come from a common location and thus sees a virtual image.

In the case of real images, the light rays truly cross. Where they cross, an image is formed, and this image can be projected onto a screen. A real image can only be viewed via a screen. How, then, could you see the *real*, upside down image in the concave mirror when you viewed your own image from far off? The retina of your eye provides the screen for the light rays to focus on, allowing you to see the image. You can only see real images in this manner when you are standing at the precise location where the rays are converging. If you stand at any other point, it is like having a slide projector but no screen. No image of that object will be seen.

So what is happening at the point where the image is whited out? If a far object's reflected rays converge to form a real image, and a close object's reflected rays diverge forming a virtual image, there must be a point where the rays neither converge nor diverge, but rather are exactly parallel. Here, no image at all forms. This spot is called the **focal point**.

Light rays which come from an object located at the focal point will reflect off the mirror parallel to one another. Interestingly, light coming from an object so far away that the rays are parallel to one another will form an image at the focal point. Thus, by aiming a concave mirror at a far-off object and locating where the image forms, you are determining the focal point of the mirror.

If you could see the entire sphere that a particular mirror was cut from, you could easily find out the focal point. The radius of the sphere is exactly twice the focal point distance; thus if a mirror were made by silvering the inside of a glass globe of radius 30 centimenters, the focal point distance of that mirror would be 15 centimenters from the mirror. A mirror made by silvering the back of the same glass globe would have a focal point distance of –15cm; that is, the focal point is 15 centimenter from the mirror but on the "wrong" side of the mirror. This trick will come in handy when you are predicting where an image will be located.

5.5 The Mirror Equation

The mirror equation can be used to predict where an image will form for a particular mirror and a particular distance that an object is placed before the mirror. For a mirror of focal point distance **f** with an object placed a distance d_o from the mirror, d_i represents the distance the resulting image is from the mirror.

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$$

All values on the proper side of the mirror are positive, while values on the "wrong" side of the mirror (where no physical object could truly be) are negative. Thus a concave mirror has a positive focal point distance, since the center of the sphere --and thus the focal point – is in front of the mirror, while a convex mirror has a negative focal point distance, since the center of that sphere is behind the mirror. Object distances are always positive, since you never place an object behind a mirror. Image distances are positive for real images, which form on the proper side of the mirror and can be focused onto paper. Image distances are negative for virtual images, which are seen to exist "inside" the mirror, where no physical object could truly be.

5.6 Magnification

The size of the resulting image can also be determined with knowledge of the type of mirror and the object itself. Magnification can be calculated by using the object distance, which is pre-determined, and the image distance, which can be obtained via the mirror equation. For a given object distance, d_o, and image distance, d_i, the magnification of the image, **M**, will be as follows:

$$M = -\frac{d_i}{d_o}$$

But magnification is simply how large the image is compared to the original object, so it can also be written:

$$M = \frac{h_i}{h_o}$$

where h_i is the image height and h_o is the height of the original object. A negative height means the object is inverted; since only real images are upside down, this method will also tell you if you have a real image, and thus will confirm whether you have a concave mirror or not. A positive height with a magnification greater than one means an enlarged, virtual image, which indicates a concave mirror. A positive height with a magnification less than one means a reduced, virtual image, which must have come from a convex mirror.

5.7 Pyromania I: Mirrors

Just like coal or oil can be converted into heat energy by burning it, so similarly can light be converted into heat energy with the use of a concave mirror. Recall that a concave mirror forms a real image when the object is farther from the mirror than the focal point distance. This is due to the fact that the light rays being reflected by the mirror really cross, focusing at a particular location in space.

Generally, the amount of light (and energy) coming from a particular object is not much. However, when a concave mirror is aimed at the sun, there is so much energy being focused to such a tiny location, that a piece of paper placed at the right spot receives enough energy to start smoldering and then burning. The sun's rays arrive at the mirror almost parallel to one another, so when they reflect, they all converge at the focal point of the mirror. This is the special location at which the paper must be positioned.

5.8 Funhouses

Funhouses designed for small children often have mirrors which give you a seriously distorted image of yourself. You may have a neck which is two feet long, or no middle at all, or both. A quick examination of such mirrors shows that they are a combination of convex and concave mirrors. The image of the neck which was too long was due to the concave top of the mirror which produced a magnified, upright image from the light coming from your neck. When you looked into the middle part of the mirror, you were looking into a convex mirror, which made images upright but much smaller than the original objects being viewed. By varying the type and curvature of the mirrors, the makers caused different alterations to be given to your image, often to the point where it is hardly recognizable as your own.

5.9 Anamorphic art

Look into a convex mirror and you will see a distorted view of the scene around you. Now imagine designing a piece of art which, when viewed via that same mirror, is seen *undistorted*. This is **anamorphic art**. The subject of the actual artwork appears deformed unless it is viewed with the help of a mirror or from a particular, skewed perspective. Such artwork was popular in Shakespeare's time; in fact, in one of his works he describes such a piece:

"Like perspectives, which rightly gazed upon,
Show nothing but confusion, eyed awry,
Distinguish form."

There are several types of anamorphic art, each dependent upon the method needed to translate them into understandable images. The type which requires a cylindrical mirror—which is not too different from a spherical, convex mirror—is one of the easiest to produce, requiring only a grid somewhat resembling polar coordinate graph paper. Just like a shop anti-theft mirror takes an entire room's worth of images and pushes them into a tiny space, the cylindrical mirror takes the expanded drawing and packs it into a compact image. In the latter case, however, the image begins deformed and ends clear, whereas with the theft mirror, the opposite is true.

Another type of anamorphic art uses a conical decoder mirror. The original art for these works is particularly indecipherable without the accompanying mirror, as the outermost part of the picture becomes the innermost part of the image. These may also be made with a corresponding grid, though a common method is to use photographic equipment.

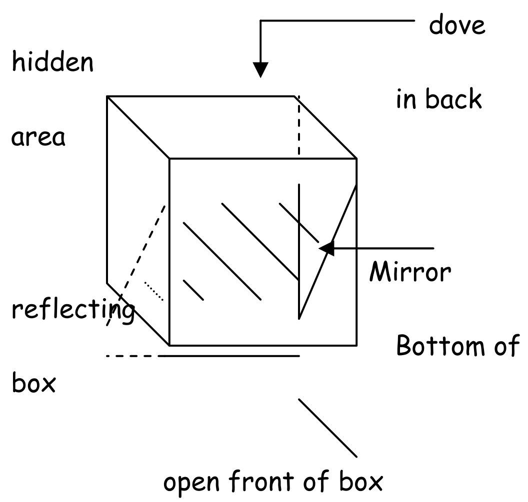
A third type of anamorphic art, particularly popular in the risqué Victorian era, is made to be viewed without a mirror at all. When viewed on edge, a greatly elongated picture can be seen in its undistorted form. This was used in Hans Holbein's painting "The Ambassadors." When seen head-on, the painting merely has an odd set of streaks. The additional image of a skull is only seen in its true form when viewed from a glancing angle.

5.10 Magicians' Tricks

Over the years, magicians have impressed and amazed their audiences by pulling objects from empty boxes, causing people to disappear, and creating talking head illusions. Toys sold in magic shops boasted of being x-ray machines that allow the viewer to see through any object. All of these inventions require only the cunning use of mirrors to make them work.

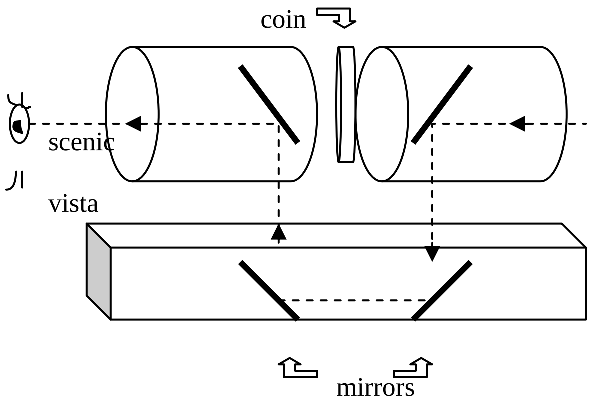
The magician opens the front flap of the box to show the audience that the box is empty. Sure enough, there is nowhere anything larger than an ant could hide; the box is obviously empty. The magician closes the flap again, perhaps covers the box with a silk cloth, intones some impressive gibberish, and, whipping off the silk, opens a top flap of the box and pulls out a white dove, which then flies in dramatic circles about the room. The audience of six-year-olds gasps in surprise and disbelief.

The trick is almost boring once you take a peek into the mechanics of the box. The picture below shows how a mirror is used to fool the audience into thinking that a box containing a dove is empty.



The mirror is positioned to reflect the bottom of the box so that the audience believes it is viewing the entire box when in actuality only half of the box is visible. Turn the box sideways and have a person sitting in the hidden region with their head extending out through a hole in the top of the box, and the talking head illusion has been created.

The x-ray toy is nothing more than two pair of mirrors aimed at 45 degree angles to shunt the light around the object (such as a coin) while making the viewer think the light is traveling a straight path.



The viewer expects to see the tube blocked by the coin, but instead, she sees the scenic vista on the other side of the cylinder.   Basically, this toy is like a pair of periscopes linked together.

5.11 Problems to Do:

1. What is the law of reflection?

2. a) What is the incident angle?

   b) What is the reflected angle?

3. How are angles measured?

4. What determines if a surface will give a specular or a diffuse reflection?

5. How far behind a flat mirror will your image seem to be if you stand 1 meter in front of the mirror?

6. Why do things seem reversed when they are seen in a mirror?

7. What is a virtual image?

8. When you look into a bathroom mirror, are you looking at a virtual image?

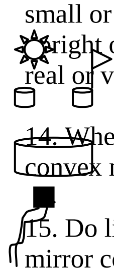
9. Name three places you will see virtual images.

10. Describe how to make a kaleidoscope.

11. Why must the mirrors be placed at an angle from one another that is an integral factor of 360?

12. What does a convex mirror look like?

13. Are images seen in a convex mirror:
small or enlarged?
upright or upside down?
real or virtual?



14. Where are two places that commonly use convex mirrors?

15. Do light rays which reflect off a convex mirror converge or diverge after reflection?

16. Can a virtual image be seen by a human eye?

17. Can a virtual image by photographed?

18. Can a virtual image be focused directly onto a screen similarly to how slides are focused onto a screen?

19. What is the name given to a mirror shaped like the inside of a spoon?

20. What type of image will be produced if you stand very close to a concave mirror:
Real or virtual?
Small or enlarged?
Upright or upside down?

21. How do you know if an image is real or virtual?

22. What happens if you stand at the focal point distance and look into a concave mirror?

23. What type of images are seen if you stand farther than the focal point distance from a concave mirror?

24. What happens to the light which comes from the focal point distance after it reflects off a concave mirror?

25. What is the mirror equation?

26. What can the mirror equation be used to find out?

27. When is the focal point distance considered to be negative? When is it positive?

28. When is the image distance considered to be negative? When is it positive?

29. When is the object distance considered to be negative? When is it positive?

30. You stand 10 cm in front of a convex mirror of focal point -5.0 cm. You do not need to convert distances to meters.
a) What is the image distance?
b) Does the image seem to be in front of the mirror or behind it?
c) Which is closer to the mirror: object or image?
d) Is the image real or virtual?

31. A candle is placed 50 cm in front of a mirror. Its image appears to be 75 cm **inside the mirror**.
a) Is the image real or virtual?
b) What is the focal point of the mirror?
c) Is the mirror convex or concave?

32. A picture is held up to a concave mirror. The picture is 1 meter away from the mirror. The focal point distance of the mirror is 2 meters.
a) What is the image distance?
b) Is the image in front of the mirror or behind it?
c) Is the image real or virtual?

33. The same picture is held 4 meters away from the same concave mirror as question #32.
a) What is the new image distance?
b) Is the image in front of the mirror or behind it?
c) Is the image real or virtual?

34. The same picture is held 1 meter away from a convex mirror of focal point –2 meters.
a) What is the image distance?
b) Is the image in front of the mirror or behind it?
c) Is the image real or virtual?

35. The picture is held 4 meters away from the same convex mirror as question #34.
a) What is the new image distance?
b) Is the image in front of the mirror or behind it?
c) Is the image real or virtual?

36. What are the two magnification equations?

37. What does it mean if the height is negative?

38. What does it mean if the magnification is less than one?

39. What does it mean if the magnification is equal to one?

40. What does it mean if the magnification is negative?

41. How can you use magnification to determine which type of mirror you have?

42. How can a mirror be used to start a fire? Be specific regarding mirror type and location of screen!

43. Why does the above procedure work?

44. How do funhouse mirrors create such peculiar images of people?

45. What is anamorphic art?

46. Explain one type of anamorphic art.

47. Explain a second type of anamorphic art.

48. Explain a third type of anamorphic art.

49. How can a magician make a dove suddenly appear in a previously empty box?

50. What changes could be made to the dove trick to make it appear as though a “decapitated” head were able to talk to an audience?

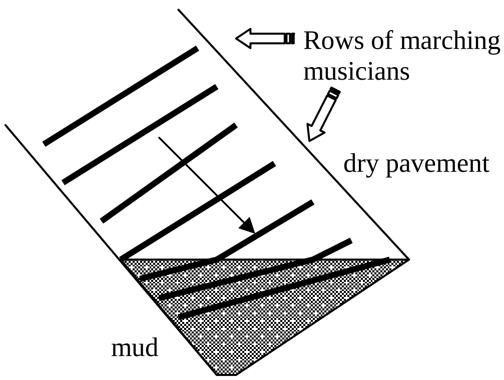
51. How does the “x-ray” toy work?

6. Physics in the Arts

Bending Light

6.1 Refraction

Imagine the Hinsdale Central Marching Band performing for the Homecoming parade. They are all in perfect rows, moving exactly in time with one another as they march along. Then they reach a section of the roadway where a recent downpour has caused mud to form. Those still marching on dry pavement continue to move forward unaffected. Those who march on mud can't move as quickly. The rows bend.



marchers slow down in the mud, causing the rows to bend

Think of light as acting the same way. When it moves from one material to something denser, such as from air to water, the light can't travel as fast in the new material. The distance between successive wave crests shortens, making the wavelength itself shorter.

If the light rays enter perpendicular to the boundary (straight on), then the change in the wave length is not noticed. However, if the rays are entering at an angle, some wave lengths of light will be affected sooner than others. Just as the rows of the marching band bent at the mud boundary, so the light bends as it enters the new medium. This bending is called **refraction**.

If you put a pencil in a glass of water, you will notice that the pencil seems to be bent right at the air-water boundary. Remove the pencil, and you can verify that it is still straight. This is an example of refraction.

6.2 Speed of Light

Earlier we learned that the speed of light is **c**, or 3 x 10^8 m/s. In actuality, this is only true for light traveling in a vacuum, such as space, where there is nothing to inhibit the motion of the light. In all other media, the light must be absorbed and re-emitted, which takes time. Thus, light moves slower in air or water or diamond or even jello than it does in outer space. The **index of refraction** of a medium is a measurement of how difficult it is for light to move through that material. Every material has its own index of refraction. Represented by the letter **n**, the index of refraction is a unitless number.

medium	Index of refraction (**n**)
vacuum	1.000000 exactly
air	1.0003 (close to 1)
ice	1.31
water	1.33
glass	1.5
diamond	2.42

The speed of light and the index of refraction are related in the following way:

$$n_1 v_1 = n_2 v_2$$

where: n_1 **= index of first medium**
n_2 **= index of second medium**
v_1 **= speed of light in first medium**
v_2 **= speed of light in second medium**

Since light travels at its fastest in a vacuum where nothing inhibits its motion, the largest value **v** could have is that of **c**, at which point **n** is equal to 1. Similarly, the smallest the index of refraction can ever be is one, since it will always be easier for light to go through a vacuum than through any other material.

<u>6.3 The Invisible Man</u>

In a novel called <u>The Invisible Man</u>, by H.G. Wells, the protagonist finds a way to become invisible. But that's impossible, right? Well, not entirely. When two materials have identical indices of refraction, light passing from one to the other cannot distinguish the boundary between them. Light will not alter its path if it does not recognize a boundary as existing. Thus, if the Invisible Man could cause his skin's index of refraction (which must normally be quite high, since light does not readily pass through it at all) to match that of the air around him, light could pass through him without changing its path. It would not reflect off him, to be seen by other eyes. It would not refract as it passed through, either. There would be no way of telling he was standing there.

It is quite possible for two materials to have the same index of refraction. Mineral oil and plexiglass have such similar indices that a chunk of plexiglass will disappear in a bottle of mineral oil. You could look through the bottle and swear there was nothing but a clear liquid present. The Invisible Man would have to do something similar to his skin with respect to the air. But it's one thing to find two materials that happen to have the same index of refraction, and another thing entirely to cause a material's index of refraction to change. Could he accomplish this?

Perhaps he could. If you take an ordinary sheet of newspaper and hold it up to the light, the paper is fairly opaque, allowing little light through. However, place a few drops of water on the newspaper and watch what happens to the opacity. The addition of water has caused the index of refraction to become much closer to that of air, making the paper more transparent than it was. But if we can alter the index of refraction of a newspaper, what is to prevent us from altering the index of refraction of our bodies? Theoretically, it is just possible that such a thing could be accomplished. Perhaps the Invisible Man isn't a story of science fiction, but of science future. Perhaps.

<u>6.4 Snell's Law</u>

We can determine which direction the light will bend, and to what degree, by using the index of refraction. The equation relating the angles and the indices is called **Snell's Law**.

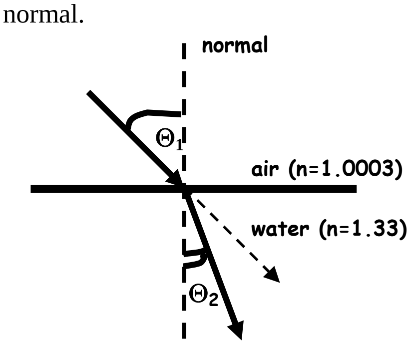
$$n_1 \sin(\Theta_1) = n_2 \sin(\Theta_2)$$

where:

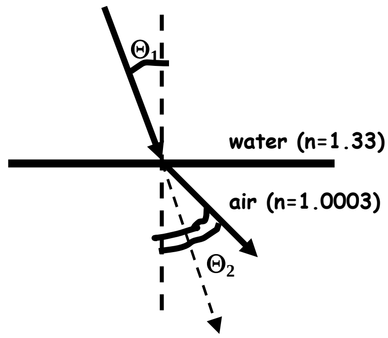
- n_1 = **index of refraction of first medium**
- Θ_1 = **incident angle, measured from normal**
- n_2 = **index of second medium**
- Θ_2 = **<u>refraction</u> angle (new angle)**

All angles are measured from the normal which, as with mirrors, is measured from the surface. In this case, the normal to the surface is the line perpendicular to the boundary between the two different layers.

Examine the equation for just a moment. Since the two sides of the equation must be equal, a moment's thought will show you that when n_1 is smaller than n_2, $\sin(\Theta_1)$ must be larger than $\sin(\Theta_1)$. But as the sine function increases, so does the angle. Therefore, when light goes from a sparse medium into a dense medium $(n_1 < n_2)$, the incident angle must be larger than the refracted angle $(\Theta_1 > \Theta_2)$. Recalling that all angles are measured *from the normal*, this means that <u>when light enters into a denser material, it will bend towards the normal</u>, whereas when it enters a sparser medium, it will bend away from the normal.



Light moving from a sparse medium (air) into a dense medium (water) bends towards the normal.



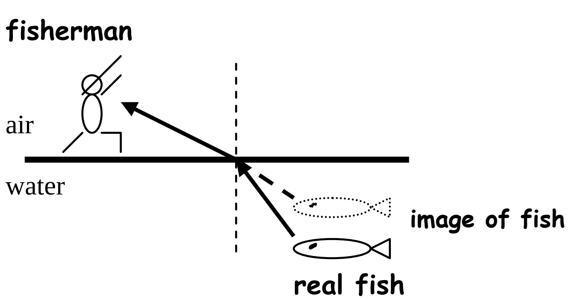
Light moving from a dense medium (water) into a sparse medium (air) bends away from the normal.

Snell's Law and refraction can help us explain such oddities as mirages, rainbows, and fibre optics.

6.5 Harpooning Fish

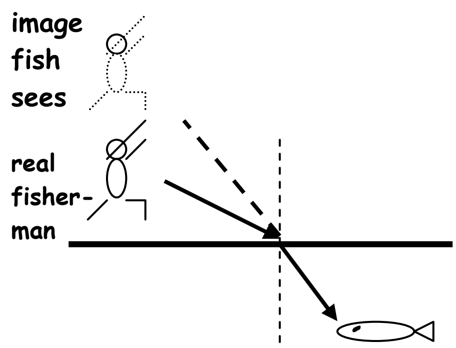
A member of a hunter-gatherer tribe stands poised at the edge of a lake, spear in hand. He waits absolutely motionlessly until a fish swims into just the right spot. Then, with a swift movement, he stabs the harpoon directly at the fish, and….misses?

One of the implications of refraction is that when you look from one medium into another, the place where you think you see the object is not where it is really located. In the above fishing example, the light from the fish, upon leaving the water and entering the air, was bent away from the normal. This means the watching fisherman saw the fish closer to the surface than the fish truly was. To catch the fish, the fisherman must aim below where the fish appears to be.



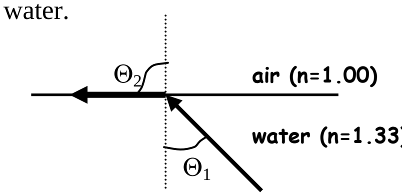
The fisherman sees the light coming from a low angle, and thinks the fish is near the surface.

If the fisherman sees the fish as being shallower than it actually is, it is reasonable that the fish might see the fisherman as being higher in the sky than he actually is, and this proves to be the case. To show this, reverse the light's path so that it is leaving the fisherman and arriving at the fish. The fish sees the light as coming from a higher angle than it should, so it sees the fisherman's image higher in the sky than the fisherman truly is.



The fish sees the light coming from a high angle, and thinks the fisherman is high in the air.

But the fish's world has other oddities. Imagine swimming under water and aiming a flashlight up towards the surface. If it is aimed nearly vertically, someone above the surface could see the light. However, there is an angle the flashlight may be aimed such that the light bends so much that it doesn't actually enter the air at all. Instead, it is bent back along the surface of the water.



This special angle is called the **critical angle**. For water, the critical angle is 48.8 degrees.

$$n_1 \sin(\Theta_1) = n_2 \sin(\Theta_2)$$

$$1.33 \sin(\Theta_1) = 1.00 \sin(90^\circ)$$

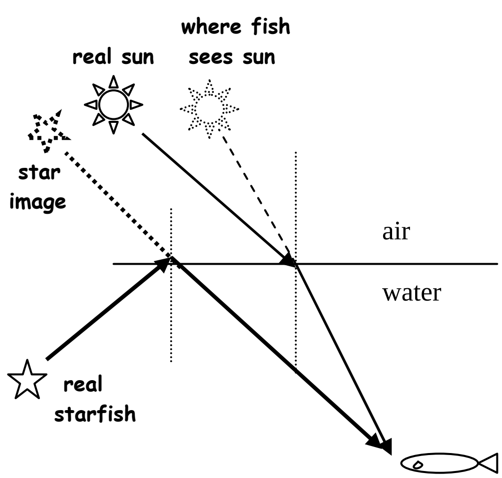
$$\sin(\Theta_1) = \frac{1.00\ (1)}{1.33}$$

$$\Theta_1 = \sin^{-1} (1/1.33)$$

$$\Theta_1 = 48.8°$$

Light rays aimed closer to the normal than 48.8 degrees will refract into the air. Light rays aimed at an angle greater than 48.8 degrees will reflect. Thus the water acts like a mirror for all rays which strike at the critical angle or larger. When the light reflects off the boundary instead of bending through to the other material, it is called **total internal reflection**.

Consider a fish observing the world around it. Objects in the air above the fish would appear higher than they should be. Other objects, such as a starfish on the seafloor below the fish, would have reflected images up high and yet could be viewed directly as well.



Light from the sun refracts; Θ is less than 48.8°. Light from the starfish reflects; Θ is greater than 48.8°.

Think how confused that fish must be. It sees not only a starfish up in its "sky," but another one when it looks straight ahead! It lives in a world fraught with objects that aren't where they appear to be.

6.6 Telephones

Total internal reflection comes in quite handy in areas such as communications. Originally, telephone cables had to be coated and separated from one another, for fear that crossed wires might cause conversations to cross as well. This procedure takes up a lot of physical space, so the more phone lines a neighborhood required, the thicker the cables strung in that area would be.

However, when light is sent through a solid cable at the material's critical angle, the light will reflect down the entire length of the cable, bending when the cable bends, with none of the light able to escape or deviate from the cable until it reaches the other end. State-of-the-art materials allow the cables to have diameters no bigger around than a hair on your head. Thus numerous cables can be abutted next to one another in a tiny space without danger of information crossing from one line to another. The science of using such cables and total internal reflection is called **fibre optics**.

6.7 Fibre Optics' Myriad of Uses

An interior decorator, an auto mechanic, and a surgeon all make use of fibre optics in their work. Vases with fibre optics tubes dangling like cut flowers grace many a fireplace mantel. The wires in these light lamps create an unusual display by allowing light entering from within the base to exit only at the ends.

Curved tubes called snake lights are used by auto mechanics to put light exactly where they need it. Using total internal reflection, the tubes reflect light down their lengths, losing none of its intensity along the way.

Surgeons use scaled down versions of snake lights during surgery. Instead of cutting open the patient in huge swathes, the surgeon makes a tiny incision and inserts fibre optics cables, which send light down and illuminating images of what is inside back up.

6.8 A Girl's Best Friend

Not many people can afford to decorate their houses with diamonds, but each time they decorate their person with them, they are wearing an example of total internal reflection. Most gemstones reflect back to the viewer only a small percentage of the light rays which strike them. Properly cut and polished diamonds, on the other hand, reflect all of the light that enters their top surfaces, giving rise to the term "brilliant cut." The facets of a diamond cleaved in the brilliant cut shape are at the angle that causes light entering it to experience total internal reflection. The light bounces off interior surfaces until it is sent back out the top of the stone to the viewer. The exiting light, having lost none of its strength to refraction out the facets, is much stronger than the light leaving other gemstones. Thus diamonds have much more sparkle than other gems.

6.9 Shimmering Sidewalks and Twinkling Stars

On a hot summer day if you observe a typical sidewalk, you will see the air shimmer and shift like a live thing. This is another example of refraction. The temperature of the air will affect its density, and thus its index of refraction. As light travels through the air to strike the sidewalk and reflect back to your eye, it is being continually refracted. Its angle is changing subtly as it passes through each different temperature of air. But breezes near the ground can easily move the air around, so the light does not refract the exact same direction all the time. This means the image doesn't remain in the same spot. This is the origin of the shimmering sidewalk. The amount of refraction is constantly changing, and therefore the image is continually changing its location.

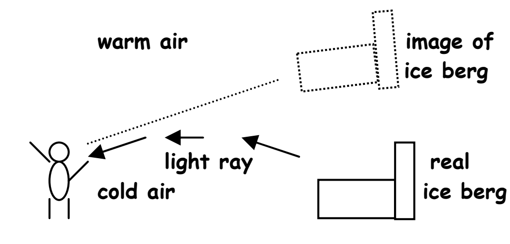
This is also the explanation of why stars twinkle. As the light from the star travels through our atmosphere, different temperatures and densities of the air shift the light slightly, deviating it from its original path. This slight shifting is enough for an observer to see the star one moment, but have the image refracted out of view the next. This makes the star appear to twinkle. Planets, which appear larger in our sky than stars do, do not show this twinkling.

6.10 Fata Morgana and other Mirage

Fata Morgana is an excellent example of art in nature. In regions of the world where there are icebergs and ice floes, an illusion of huge ice columns and ice castles are sometimes seen. These are not hallucinations, but rather mirage.

Just like light bends as it goes from air to water, it also bends as it goes from warm air to cold air. Since different temperatures of air have different densities, they act as different media. Like the marching band on dry pavement, light can move faster in hot air than cold air. The marching band's neat rows bend towards the region of mud; the light's neat rays bend towards the colder air.

You first saw this phenomenon when you studied refraction of sound, and used the concept to explain why when the ground was cold, sound bend down towards the ground, while when the ground was warm, the sound bent up towards the sky. The same ideas hold true for light. Consider the ocean and ice floes again. The water and ice will be quite cold, but the air higher up could be warm. Light that leaves the ice and would normally only be seen from someone high in the sky is bent downward, towards the cold air; this light is seen by the viewer as angling downward, as though it had originated in the sky. Thus the eye is tricked into thinking the image it sees is of an object in the sky.

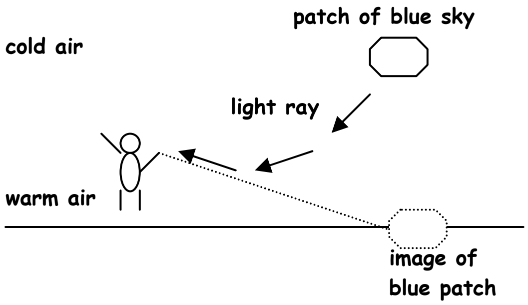


The light is bent downward, making the iceberg appear to float in the sky.

When the refracted image and original iceberg merge together, they create the tall white columns that are known as the Fata Morgana mirage, named after Morgan le Fey, the faerie sister of King Arthur. Fata Morgana is most commonly seen in the Arctic regions, such as at Thule in far northern Greenland, but it was first made famous at the Strait of Messina in Italy.

Just as cold air near the ground and warm air aloft can cause light to refract downward creating mirages in the sky, in the same manner, warm air near the ground and cold air aloft will cause objects normally seen in the sky to appear at ground level.

The most common of these mirage is the puddle on the highway, which is often seen on a hot day. Light from the blue sky that was originally aimed downward is refracted up so that a viewer sees it coming from a low angle. The eye is fooled into believing there is a patch of blue on the ground. But that's silly; the sky is never seen at ground level... except when it is reflected off a puddle. The brain concludes that it is viewing the reflection of blue sky off water, whereas in fact it is viewing refracted light from the sky.

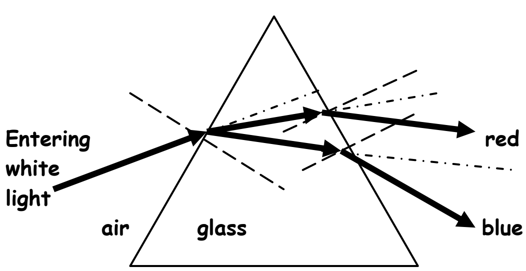


The light is bent upward, making the blue appear low. The brain interprets this as a puddle reflecting sky light.

This is the origin of the oasis mirage that is so common that it has become a cliché. The mirage is not a hallucination; it is a very real example of refraction art in nature. However, any hula dancers in the image would be a hallucination!

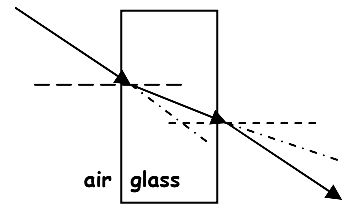
6.11 Prisms

Prisms rely on the fact that all colors of visible light do not refract the same amount upon entering a new medium. When white light, which is made up of all colors, strikes a triangular chunk of glass, the colors all enter at the same incident angle. However, since each color bends a slightly different amount upon entering the glass, the colors will separate into distinct bands, with the blue end of the spectrum bending the most and the red end bending the least. The triangular shape of the glass actually makes the light bend twice: once as it enters and once as it exits.



Because blue light bends more than red light, white light breaks into its colors when it enters glass.

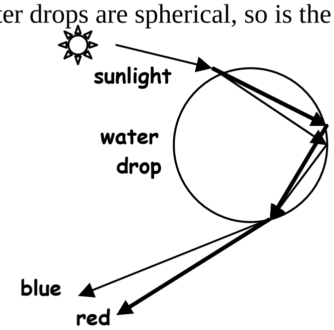
But light doesn't normally break into colors when it goes through windows. Why not? The light actually does break into its colors when it enters the window pane, but it is bent back into white light as it leaves the other side. Any time the medium has parallel sides, the light will not show bending. Going from air to glass, the light bends towards the normal; traveling from glass back into air, the light bends away from the normal.



Light bends upon entering and is bent to its original angle upon leaving since the sides of the glass are parallel.

6.12 Rainbows

Rainbows are basically millions of tiny water prisms suspended in the air. White light from the sun enters a tiny spherical raindrop, causing the spectrum of colors to separate. The light is then reflected off the back of the raindrop. Since red and blue light (and all colors in between) are bent different angles, they hit the back of the drop at different angles as well. When the light leaves the drop, only one color per drop will be angled at just the precise way so as to strike the viewer's eye. All other colors from that drop will arrive at an angle that is either too high or too low. But recall that there are millions of droplets that are involved in this refracting and reflecting. Different drops are responsible for the viewer seeing different bands of color. Since the water drops are spherical, so is the rainbow.



Different colors leave the drop at different angles.

6.13 Problems to Do:

1. What is refraction?

2. Why do the neat rows change when a marching band crosses a muddy patch in the road?

3. Why does light bend?

4. Is the speed of light a constant?

5. What is the index of refraction?

6. If it is hard for light to travel through a material, will the material's index be high or low?

7. What happens to light passing between materials that have the same index of refraction?

8. What would the Invisible Man have to do to his index of refraction to become invisible?

9. What is Snell's Law?

10. When light goes from air to glass, does it bend towards the normal or away from the normal?

11. When light goes from glass to air, does it bend towards the normal or away from it?

12. What is the critical angle for light traveling from glass into air?

13. What happens to light which strikes the boundary at the critical angle?

14. When will total internal reflection occur?

15. When you are underwater looking up at the air-water boundary, why do you see some objects twice?

16. Will a person poised above the edge of a pool appear high or low in the "sky" to a peson swimming under water?

17. How are fibre optics capabilities used in the communication industry?

18. What are three other ways fibre optics is being used?

19. Why do diamonds have the brilliant shine that they do?

20. Why do sidewalks shimmer?

21. The surface of the moon gets extremely hot during the lunar day. Would the lunar soil shimmer? Explain.

22. Why don't planets twinkle?

23. If you were on Mars, which has a thinner atmosphere than Earth and is located farther from the sun, would you observe more twinkling of stars or less twinkling?

24. Why doesn't grass shimmer?

25. What causes the fata morgana mirage?

26. What causes us to see blue skies at ground level on the highway ahead of us?

27. Concerning the previous question, why does the brain think there is water there?

28. Why does a prism break light into a spectrum while a window pane does not?

29. How do raindrops in the sky cause rainbows?

30. Light enters glass at an angle of 20 degrees from the normal.
    a) Does the light reflect or refract?
    b) What angle does it move off at?

31. Light enters glass at an angle of 50 degrees from the normal.
    a) Does it reflect or refract?
    b) What angle does it move off at?

32. What is the speed of light in diamond?

33. Recently, scientists claim they have been able to slow down light to about 17 m/s (around 35 mph). If the effect were caused solely by using a medium that light could not move easily through, calculate the index of refraction for the material they used.

34. What is the cause of mirage?

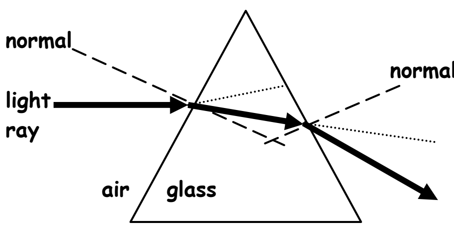
7. Physics in the Arts

Lenses and Photography

7.1 converging lenses

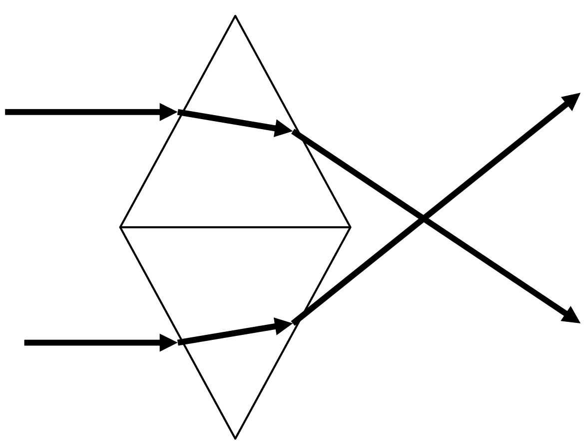
Light bends as it enters a new material. When it passes through a chunk of glass, it bends in predictable ways, creating images that are real or virtual, large or small, upright or upside down--all depending upon the shape of the piece of glass.

We saw last chapter that a triangular chunk of glass will cause light to bend toward the base of the prism.



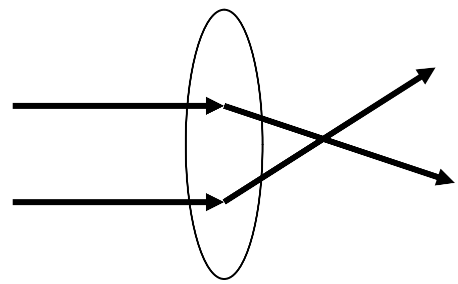
Light passing through a triangular prism bends towards the base.

Imagine putting two prisms together, with their bases next to one another. Parallel light rays entering the prisms will cross on the other side.



Rays bend towards the prism's base, converging as they leave the glass. An image forms where the rays cross.

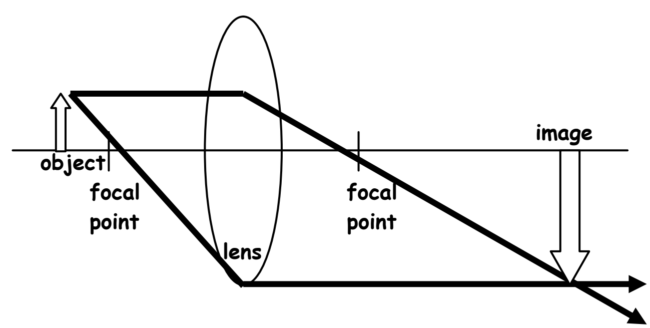
Where the two rays cross, the image will form. Now imaging taking the same prism and smoothing it into a curved surface. This is a **converging lens**. A converging lens will always attempt to bring rays closer together.



Converging lenses are thickest in the center; they try to make rays cross.

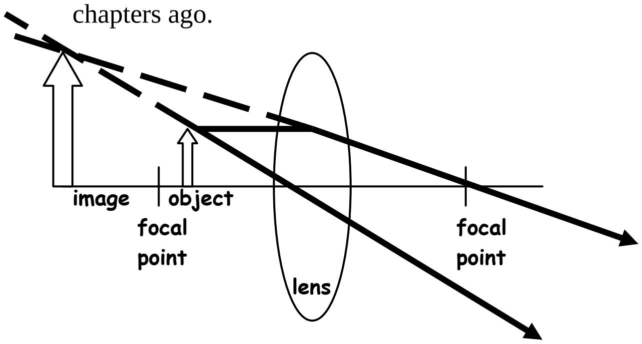
Lenses, like mirrors, have focal points. However, since they have two curved sides, they have two focal points, one on each side of the lens. This will become important as we learn how to use ray diagrams to trace light rays as the move through lenses.

The focal point is important for another reason. Light rays from a source farther than the focal point distance will converge and form a real image. Like in our mirror unit, these real images are always upside down.



Objects farther than the focal point of converging lenses create real, upside down images.

Light rays coming from sources closer than the focal point are brought closer together, but the lens simply isn't strong enough to make the rays actually cross. A virtual image forms instead. This virtual image will be upright and enlarged, very much like the images created by the makeup or shaving mirror discussed a few chapters ago.

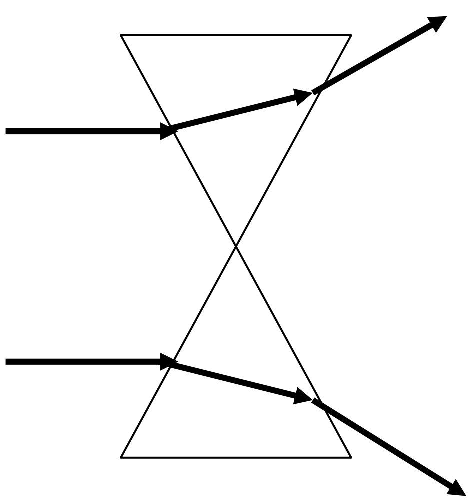


The lens is not strong enough to make the rays actually cross. Instead, an enlarged virtual image appears.

Thus, an object closer than the focal point of a converging lens will create an enlarged, upright, virtual image, while an object farther than the focal point will create a real, upside down image.

7.2 diverging lenses

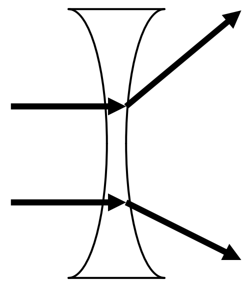
Imagine taking the same two triangular prisms as before, but placing them tip to tip instead of base to base. Now parallel light rays that enter the prisms will bend away from each other as they leave the glass.



Rays bend towards the bases, diverging as they leave the glass.

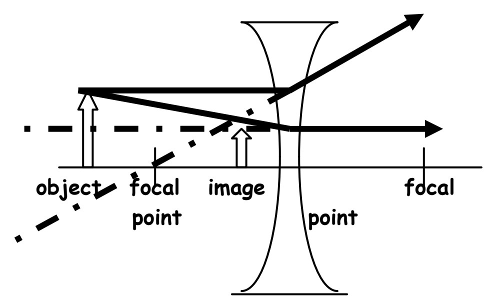
The rays never truly cross, so no real image forms. However, the light rays seem to come from a common location; that spot is where a virtual image appears.

Imagine smoothing the prisms into a curved surface, and you have created a **diverging lens**. A diverging lens will always try to spread light rays further apart.



Diverging lenses are thickest at the edges; they try to spread rays out.

As in mirrors, a virtual image appears where the light cannot truly be. With mirrors, that impossible location was behind the mirror. With lenses, the light must go through the lens in order to be bent and focused into an image; thus, the impossible (virtual) location is in front of the lens. Virtual images are still always upright. A diverging lens will create a small, virtual, upright image no matter where the object is placed relative to the focal point.



A diverging lens always creates small, upright, virtual images.

Virtual images occur whenever the lens is unable to cause the light rays to converge. Diverging rays are traced back by the eye to a location they appear to have come from. The virtual images created will have negative distances. This is similar to the virtual images created by mirrors.

7.3 The Lens Equation

Just as there is an equation to help you figure out where the image for a mirror is located, so is there an equation for locating the image of a lens. The equation is called the Lens Equation, and it looks identical to the mirror equation.

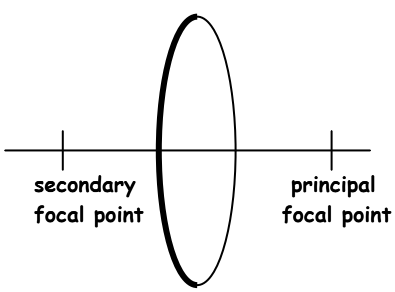
$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$$

The only difference deals with the meanings of the negative signs. Virtual image distances are still negative, but this time they are located on the same side of the lens as the object is. It is still the "wrong" side, though, since light *must* have gone through the lens to form any image at all.

By the same token, real images have positive distances and are located on the opposite side of the lens from the object, since that is where the light truly traveled. Heights have the same signs as before; that is, a real—upside down—image has a negative sign and a virtual—upright—image has a positive sign.

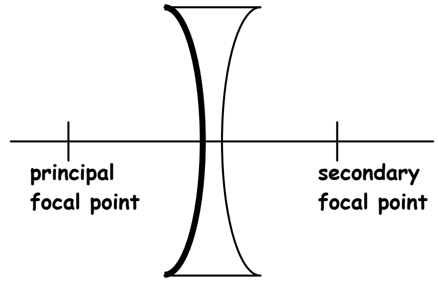
Focal point rules have new applications. Lenses have two focal points apiece: one on each side of the lens. The principal focal point is used for the equation, and it is the one which represents the surface closest to the object.

For a converging lens, which is thickest in the center, the principal focal point is on the right of the lens, which is the positive region; the light truly travels there.



The principal focal point of a converging lens is on the right; it is positive.

For a diverging lens, which is skinny in the center and thickest at the edges, the principal focal point is on the same side as the object. It will be negative, since that is the "wrong" side of the lens.

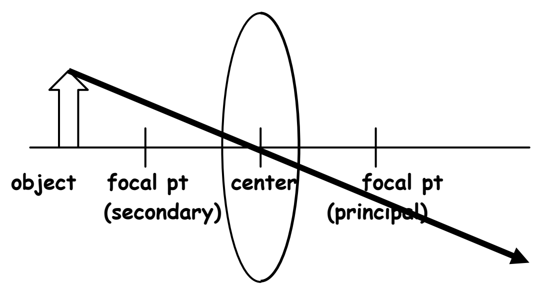


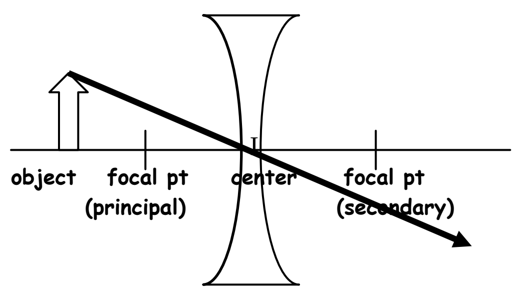
The principal focal point of a diverging lens is on the left; it is negative.

7.4 Ray Diagrams

Although the lens equation can be very valuable in determining where an image will appear, the same information can be gained by tracing the path of the light through the lens. This is called a **ray diagram**. There are three special light rays which we can draw without using a protractor or a calculator.

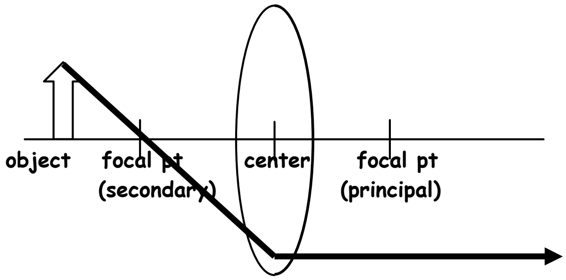
1. The center ray is not bent.

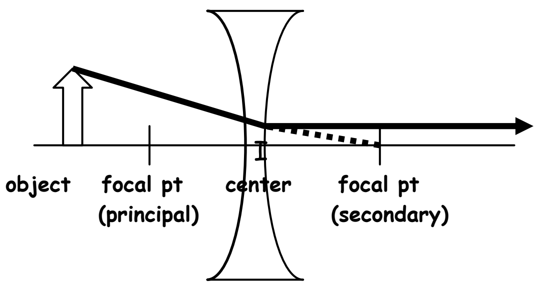




The center rays for the two lenses look identical. They rays do not bend because at the center of the lens the sides are nearly parallel. It is similar to a window pane; how ever much the light bends upon entering the glass, it is bent back upon leaving.

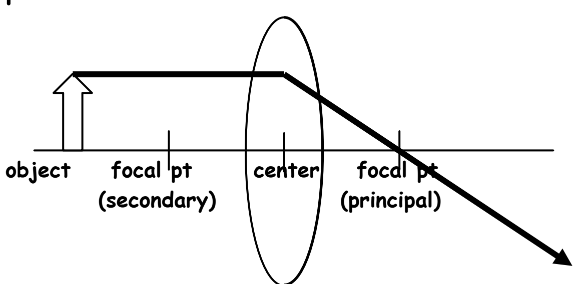
2. The ray through the secondary focal point comes out of the lens parallel.

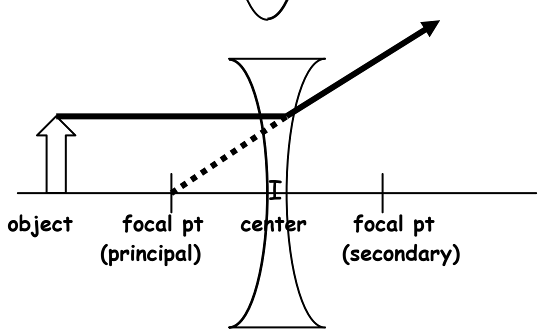




Because the secondary focal point of a diverging lens is on the right hand side, to apply rule number two, you must aim the light towards the secondary focal point and then, when the ray reaches the lens, make it bend so that it is parallel to the base line.

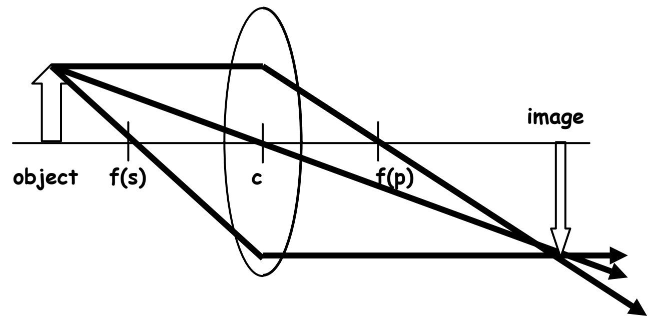
3. The ray that goes in parallel will be bent out through the principal focal point.



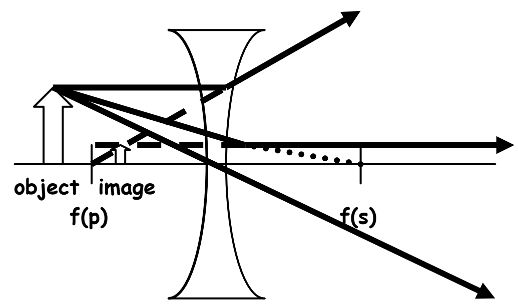


For a diverging lens, the principal focal point is on the wrong side of the lens; to apply to rule, you must bend the parallel ray directly away from the principal focal point.

To find the image of either a converging or diverging lens, draw any two of the three special rays. The image is either where the rays cross (real images) or where the rays appear to come from (virtual images).



A converging lens creates real images for objects farther than the focal pt.



A diverging lens creates small,virtual images for all object distances.

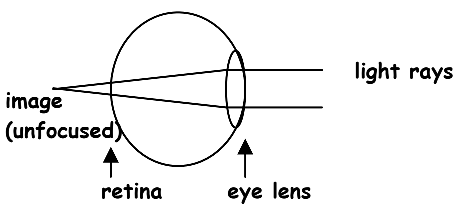
7.5 Pyromania II: Fire From Ice

In the mirrors chapter, we discussed how you could use a concave mirror to create a fire by focusing it on the sun and placing a sheet of paper at the mirror's focal point. A converging lens will act the same way. If the lens is focused on the sun and the paper is placed at the lens' principal focal point, the concentrated energy will be enough to start the paper smoldering. If left long enough, the paper will begin to burn.

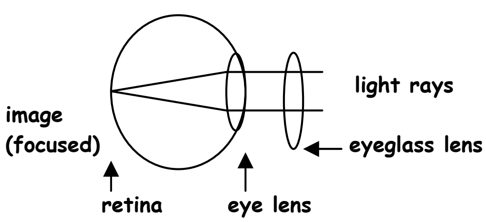
But if all that is required is to have a material which is a solid in the shape of a converging lens, what is to prevent us from using ice as a lens? Water can be frozen into the proper shape by using a mold, and so long as significant melting does not occur during the experiment, the resulting ice will make an excellent lens. Aim the lens at the sun, place a sheet of paper at its principal focal point, and voila′! Fire will be created using ice.

7.6 Nearsightedness and Farsightedness

Light forms an image when it passes through a lens. When the lens in question is your eye and the image forms just where the retina is located, you see a clear picture. However, sometimes the eyeball is short, placing the retina too close to the lens. This is the case of **farsightedness**. The image forms beyond the retina. To correct this, a converging eyeglass lens will make the image form sooner.

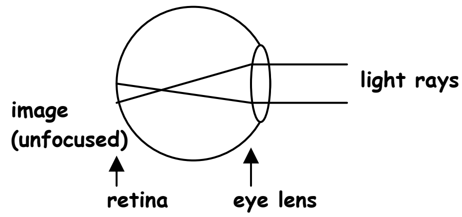


For a short eyeball, the rays do not converge soon enough, so images focus past the retina.

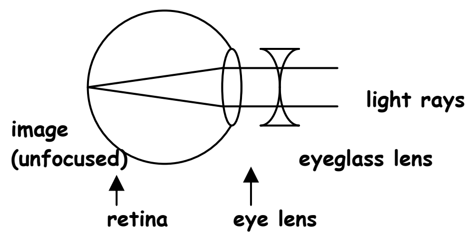


A converging lens brings the rays together so images focus sooner.

Sometimes the eyeball is too long, placing the retina too far away from the lens to properly focus the image. This is the case of **nearsightedness**. The image forms in front of the retina. To correct this, a diverging lens is placed in front of the eye, making the rays spread apart and form the image later.



For a long eyeball, the rays converge too soon, so images focus in front of the retina.



A diverging lens spreads the light rays to make the images retreat.

7.7 Pyromania III: Lord of the Flies

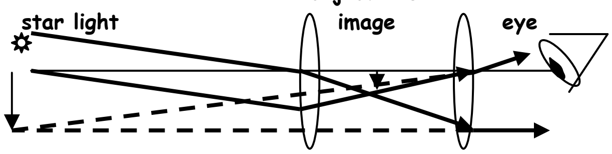
In the novel Lord of the Flies, the boys used a pair of eyeglasses to create a fire, attempting to make practical use of the principles explained in the section above. The young man whose glasses were used ("Piggy") was farsighted. Farsightedness, as is discussed in the previous section, is corrected using converging lenses. Since only converging lenses can create real images, a nearsighted person's glasses will never create fire. How fortunate for the stranded boys that Piggy wasn't nearsighted!

7.8 Astigmatism

Another eye condition which causes people to see imperfectly is **astigmatism**. Astigmatism is when the cornea (lens) of the eye does not have the same curvature everywhere. This means that light rays entering different parts of the eye will focus at different locations. The result is a fuzzy image. Sometimes a lens with different curvatures in different directions can be used to correct astigmatism.

7.9 Telescopes: Astronomical and Terrestrial

A telescope is an instrument that is used to observe objects that are quite far away. They consist of at least two lenses, both converging. The first converging lens creates a real image of the object. This image is then placed closer to the second lens than its focal point, causing the final image to be enlarged.



Light passes through the objective lens, forming a real image. The light then goes through the eyepiece, which enlarges the image.

The objective lens alone will give you an image, but that image will be quite small, and it will require a screen for viewing. The eyepiece lens is placed so that images formed by the objective lens are inside the eyepiece's focal point. This creates an enlarged, virtual image which the eye can easily interpret. This is an **astronomical telescope**.

The objective lens of an astronomical telescope creates a real, upside down image, which is then enlarged by the eyepiece. Thus, when you look through a telescope objects appear larger than when seen to the naked eye, and those images are upside down. Fortunately, when you are viewing the skies, you can simply turn star maps upside down to match telescope images to their map counterparts.

There are some circumstances when an astronomical telescope will not provide acceptable images. Consider the case when you wish to observe something far away and see the images upright. A case in point is birdwatching. Most birdwatchers would be somewhat annoyed to find themselves watching their prey upside down. Certainly it is possible to hold the bird manual upside down to match what you are observing, but watching birds in flight while they are upside down would be unnerving to say the least. Therefore, **terrestrial telescopes** (also called **binoculars**) add a set of prisms or mirrors whose sole purpose is to flip the final image over. The resulting images are right side up but fainter, since some light will reflect away each time the rays strike a new surface.

7.10 Cameras

In many ways a camera is similar to the human eye. There is a lens, just like we have lenses in our eyes. The film is like the retina; both must be located where the rays converge in order to have a perfectly focused image. The aperture is like the pupil, regulating light amounts. The shutter is like the eyelid, closing off the light entirely. The camera's benefits are twofold. First, it provides us with images which are more permanent than those placed briefly before us on our retinas. Second, the camera allows us to change the size and detail of images.

Cameras come with a variety of lens types. Wide angle lenses (lenses with a focal point of less than 28mm) create pictures in which the images are tiny and closely packed together, covering a wide range perspective. When the angle of light contributing to the photo is large enough, the horizon lines begin to look curved on the picture and the images start looking curved out of proportion. This is what happens with a fish-eye-view lens.

Have you ever noticed how large the telephoto lens attachments are? This is because a "200mm telephoto lens" has a focal point distance of 200mm (20cm); therefore, the film must be placed 20 cm behind the lens. Since cameras generally have only about 3-5 centimeters of space between the lens and film, the attachment must add the extra distance. In general, the greater the enlarging capabilities, the longer the attachment.

Finally, in the instructions which come with a camera, you are often warned about not attempting to take pictures of anything closer than about 4 feet from the camera. Recall that parallel light forms an image at the focal point of a lens; light from closer objects will strike the lens at an angle, forming images farther away than the focal point. Since the film is always placed exactly at the focal point, the resulting picture will be out of focus.

7.10 Problems to Do:

1. What is the shape of a converging lens?

2. What type of images does a converging lens create? Consider near and far object distances.

3. What is the shape of a diverging lens?

4. What type of images does a diverging lens create? Consider near and far object distances.

5. How does the lens equation differ from the mirror equation?

6. How do you distinguish a principal focal point from a secondary focal point?

7. When is the principal focal point of a lens positive?

8. When is the principal focal point of a lens negative?

9. What are the three special rays which can be drawn without using snell's law or a protractor?

10. How many rays are needed to find the image in a ray diagram?

11. When will a real image form?

12. When will a virtual image form?

13. How can you create fire from ice?

14. Why was it fortunate that Piggy from Lord of the Flies was farsighted instead of nearsighted?

15. How do you correct nearsightedness?

16. How do you correct farsightedness?

17. What is astigmatism?

18. Explain why you must use converging lenses when designing a telescope.

19. Why must the image of the objective lens be inside the focal point distance of the eyepiece?

20. What is an advantage of a terrestrial telescope? A disadvantage?

21. What is an advantage of a astronomical telescope? A disadvantage?

22. You have just purchased a 50mm lens. What does the "50mm" mean?

23. Why are 200mm lens attachments so long?

24. Why is there a minimum distance for photographing subjects?

25. You have a converging lens of principal focal point distance 10cm. If the object is located 100cm away, where will the image form?

26. For the previous question, what will the image be like?

27. You have a diverging lens of principal focal point –10cm. If the object is 100cm away, where will the image form?

28. For the previous question, what will the image be like?