Lesson 10
Properties of Light Waves

Introduction: Connecting Your Learning

The previous lesson discussed magnetism and electromagnetic induction. This lesson continues the focus on electromagnetism in the form of electromagnetic (E&M) waves. E&M waves have the unique ability to transport energy as a wave without the requirement of having a medium. This is very different than the mechanical waves studied earlier (e.g., sound waves). This lesson focuses on the basic properties of light (i.e., reflection, refraction, diffraction, and interference). An introduction to geometrical optics is also discussed.

Readings, Resources, and Assignments	
Required Textbook Readings	*Conceptual Physics* Chapter 7, Sections 7.3 and 7.4

Check Prior Knowledge

Check your prior knowledge by matching these terms.

Term	**Definition**
Ultraviolet	Portion of E&M spectrum below the visible (in frequency)
Infrared	Earth's atmosphere, for example
Wavelength	Total shadow
Opaque	Shadow of the Moon falls on the Earth
Transparent	Red, green and blue
Solar Eclipse	Make color vision possible
Lunar eclipse	Make non-color vision possible
Umbra	Portion of E&M spectrum above the visible (in frequency)
Penumbra	Metals, for example
Cones in the eye	Moon passes into the shadow of the Earth
Rods in the eye	Inversely proportional to frequency
Additive primary colors	Partial shadow

Focusing Your Learning

Lesson Objectives

By the end of this lesson, you should be able to:

1. Describe the wave phenomena of reflection, refraction, diffraction, and interference and the wave-particle duality nature of light.
2. Describe diffuse reflection, critical angle, and total internal reflection.
3. Differentiate between a real image and a virtual image.
4. Distinguish between a concave mirror and a convex mirror.
5. Describe Huygens' Principle.

Approaching the Objectives

This lesson is comprised of four sections:

Section 1: Reflection and Refraction

Section 2: Geometrical Optics

Section 3: The Mirror Equation

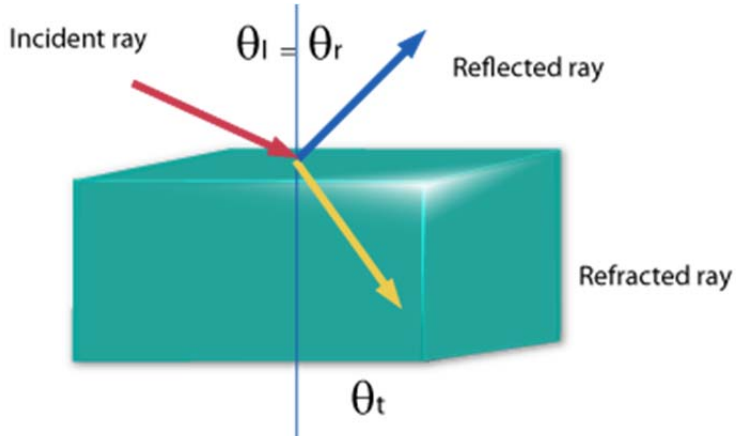
Section 4: Diffraction and Interference

Section 1: Reflection and Refraction

Start this lesson by reading Chapter 7, Section 7.3, pp. 148 to 149 in the *Conceptual Physics* textbook.

View these videos from Kahn Academy on Reflection Part 1 and Part 2 and Refraction.

When light strikes a surface, there are generally three possible results. The light may be reflected, refracted, or both. If the light is reflected, the angle of reflection is the same as the angle of incidence.



The line perpendicular to the surface is referred to as the normal. The angle, J_I is the angle of incidence. The angle, J_r, is the angle of reflection. The angle, J_t, is the angle of refraction. The angle of incidence is equal to the angle of reflection. The angle of refraction is generally less than the other two angles, because the refracted ray is bent toward the normal. Note that the angles defined above are measured with respect to the normal.

There are two basic types of reflection. In a perfect world, surfaces are completely smooth. Some surfaces, like a highly polished mirror, actually are very close to this condition. In this case, the angle of incidence is almost exactly equal to the angle of reflection. This is referred to as specular reflection.

Most real surfaces encountered in everyday life are far from being perfectly smooth. When light is reflected off a real surface (i.e., a piece of clothing, a road, a tree, etc.), the reflected ray scatters in many different directions. This is called diffuse diffraction.

Refraction, which occurs as a result of the velocity of light, varies slightly in different mediums. The ratio of the speed of light in a vacuum compared to the speed of light in the medium is referred to as the index of refraction. Light slows down when it enters a medium other than a vacuum; therefore the index of refraction will be a number greater than one. A useful relationship exists between the angle of refraction and indices of refraction. If n is the index of refraction, then the angles are related by Snell's Law, which looks like this.

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

Check understanding: The speed of light in ice is 2.29×10^8 m/s. What is the index of refraction of ice?

Solution: n = (speed of light in vacuum)/(speed of light in ice) = $(3 \times 10^8$ m/s$)/(2.29 \times 10^8$ m/s$)$

$$n = 1.31$$

Note: This quantity does NOT have units.

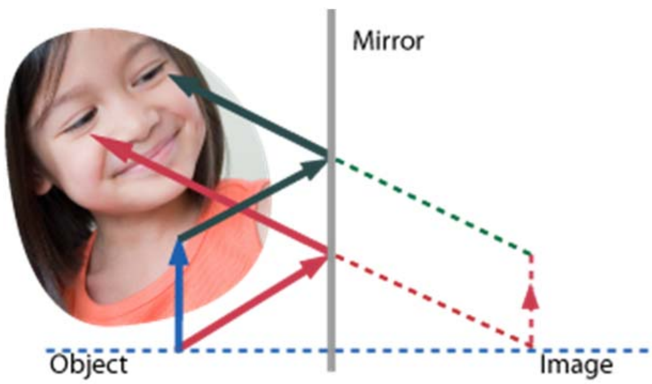
The next sections provide brief introductions to a topic that could easily take up an entire semester. Geometrical optics is all about lenses and mirrors. This section will briefly introduce the mirror equation. You will find practical application of this topic in any career that deals with optometry.

Section 2: Geometrical Optics

Start this section by reading Chapter 7, Section 7.4, pp. 149 to 154 in the *Conceptual Physics* textbook. View the videos from Kahn Academy on Virtual Image and Parabolic Mirrors Part 1 and Part 2.

There are normally two methods you can use to solve problems dealing with lenses and mirrors. One method involves geometry, and the other uses algebra and mathematical equations. Both methods should arrive at the same solution. The mathematical approach is sometimes preferred because it does not involve drawing pictures to scale. The geometrical approach is often preferred because it gives a better visual representation of what is going on. The preference in this class is to use a combination of both.

Geometrical optics starts with the premise that light behaves like a particle and a light "ray" can be drawn as a straight-line vector. When light strikes a surface, the angle of reflection is exactly equal to the angle of incidence. When you analyze a plane mirror, it is instructive to first draw a picture that represents the mirror, a receptor (i.e., eyeball), and an object. Light rays are usually drawn from two points on the object (i.e., the top and the bottom).



You can sketch the diagram, and you do not need to use a protractor to get the angles exact. Draw the rays using a straight edge and make the angle of incidence as close to the angle of reflection as possible. In the diagram above, note that the image "appears" to be coming from behind the mirror. In reality, this cannot be the case. This image is referred to as a virtual image. With a perfect plane mirror, the size of the image is the same as the size of the object. The distance from the mirror to the object is the same as the distance from the mirror to the image. The next section will illustrate that curved lenses and mirrors can possess "real" images where light actually passes through the image.

With a concave mirror (shown below), there is a point that lies along the principal axis where all light rays that strike the mirror parallel to the principal axis will converge. This point is referred to as the focal point.

Example: The mirror shown below is a concave mirror. Mirrors that curve the opposite way are referred to as convex mirrors. The object lies somewhere between the center of curvature (C) and the focal point (f).

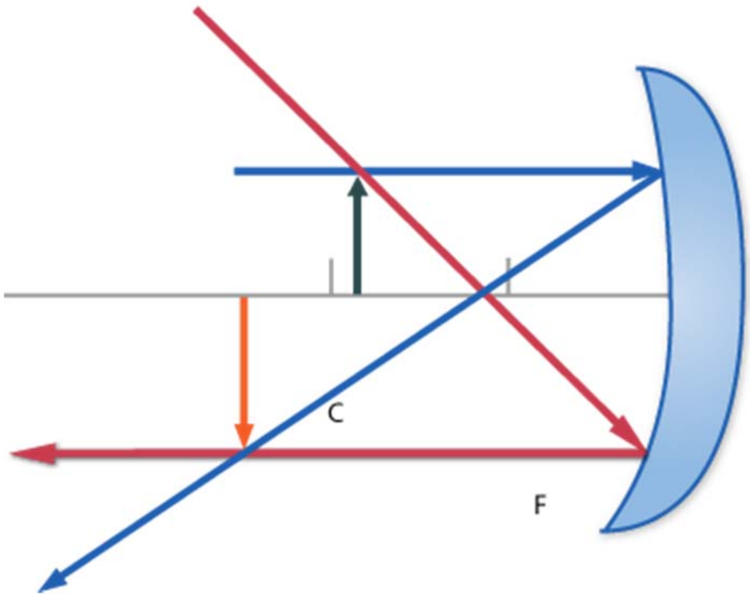
If the purpose of the problem is to find the size of the image given the size of the object and it is to be done geometrically, then you would use a ruler to measure the size of the object and set up an appropriate scale. For example, "C" is the center of curvature and "F" is the focal point. Note that F = C/2. The focal length is the distance from the mirror to the focal point. For concave mirrors, this distance is considered positive. The next step is to draw another ray that passes through the focal point and is reflected parallel to the principal axis. The intersection of the two rays shows the position of the image.

Step 1.
Make the first ray parallel to the mirror and have the reflected ray pass through the focal point (blue rays).

Step 2.
Draw a ray from the tip of the object passing through the focal point and reflected parallel to the principal axis (red rays).

Step 3.
The intersection of these two reflected rays represents the tip of the image.

In this example the image is (1) real (light passes through the image), (2) inverted (upside down), and (3) magnified (larger).



The procedure for a convex mirror is the same. Note that convex mirrors tend to produce virtual images.

View these videos from the Kahn Academy on Concave and Convex mirrors.

Section 3: The Mirror Equation

View these videos from the Kahn Academy on the Formula Proof and Image Height and Distance Relationship.

An equation can be derived from the spherical model discussed above. In words, the reciprocal of the focal length of a spherical mirror is equal to the sum of the reciprocals of the image position and the object position.

$1/f = 1/d_i + 1/d_o$

f is the focal length

d_i is the distance from the mirror to the image

d_o is the distance from the mirror to the object

Magnification (m) is simply the ratio of the image height (hi) to the object height (h_o). Using a little geometry, the magnification can be written in terms of the image and object distances.

$M = (h_i)/(h_o) = -(d_i)/(d_o)$

Example: A concave mirror has a radius of 20 cm. A 2.0 cm tall object is 30 cm from the mirror. Find the image position and image height.

Step 1. Sketch the problem. Mark the center of curvature (C) and the focal point (f).

Step 2. Write down known quantities and unknown quantities.

Known

h_o	2.0 cm
d_o	30.0 cm
f	20.0 cm

Unknown

d_i	

h_i	

Step 3. Find the focal length:

Write down the mirror equation and use algebra to solve for the image position.

Use the magnification equation and solve for the image height.

Check to see that the answer makes sense and is labeled with the proper units.

Make sure the algebraic signs on the answer make sense and are consistent with the drawing.

Challenge Problem:

An object of height (h_o) is located at (d_o) relative to a concave mirror with focal length (f). The answers can be found at the end of the lesson.

a. If the image is located twice as far from the mirror as the object, calculate the focal length as a function of object position.

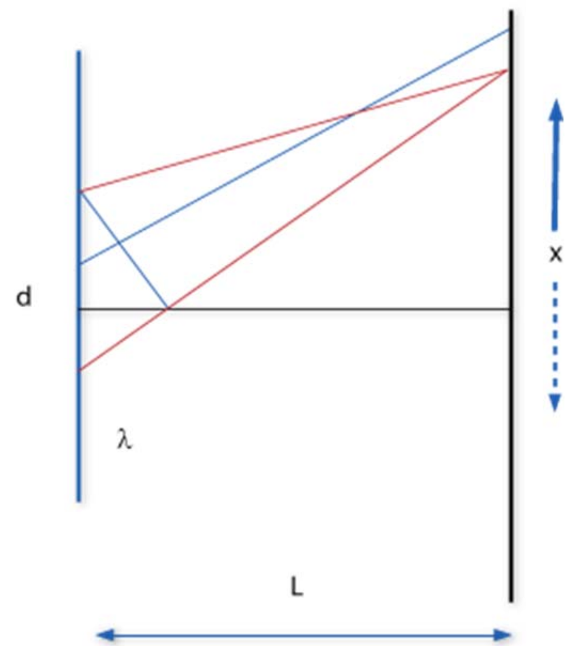
b. If the image is located twice as far from the mirror as the focal point, calculate the image height as a function of object height.

c. Where should the object be located so there is no image?

The next section discusses two other very important wave properties. Diffraction occurs when light waves bend around obstacles, and interference is about waves adding and/or subtracting when they happen to occupy the same space at the same time.

Section 4: Diffraction and Interference

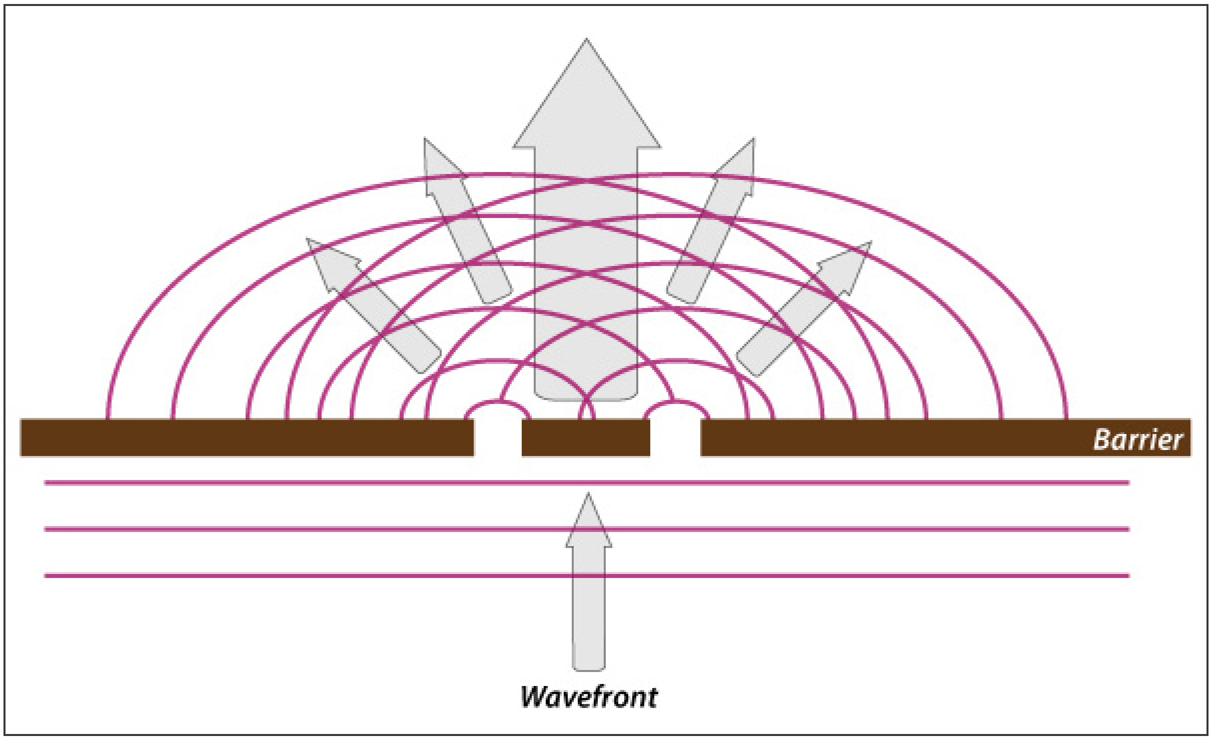
When coherent light (same frequency) is incident upon a double slit, a series of bright and dark bands appear on the screen. The bright bands correspond to constructive interference, and the dark bands correspond to destructive interference. The positions of the bands depend on the wavelength of the monochromic incident light. The double slit configuration can be used to measure the wavelength of the incident light.



In this example, λ is the wavelength of the incident light. The distance between the slits is "d". And "x" is the distance from the center of the screen to the first bright band of light on the screen. Using a little geometry, the wavelength of the light is equal to the distance on the screen from the central bright band to the first bright band, multiplied by the distance between the slits and divided by the distance to the screen, L.

$$\boldsymbol{\lambda = (xd)/L}$$

Diffraction is basically the bending of light around a barrier. According to Huygens' Principle, a wavefront of light can be considered as a series of point sources. When light passes through a slit in a barrier as shown below, the wavelets combine to form a flat wave except at the edge of the slit where the circular wavelets move away from the wave front.



A similar equation to the above for double slit interference can be derived to predict the width of the central bright band produced by the single slit diffraction pattern.

The width of the central bright band is equal to the product of twice of the wavelength times the distance to the screen, divided by the width of the slit.

**Activity:**

Sketch a diagram for a single slit diffraction scenario. Label the diagram using "w" for the width of the slit, "L" for the distance from the slit to the screen, l for the wavelength of incident light and "x" for the distance from the central bright band to the first dark band. Derive an equation that allows finding the wavelength of the incident light.

Check your answer at the bottom of the lesson.

Summarizing Your Learning

This lesson looked at various aspects of the nature of light. At times, light is considered a particle, and the geometrical properties observed can be dealt with using minimal mathematics such as simple geometry. Sometimes light is considered a v=wave, so the properties observed including interference and diffraction can be explained using simple concepts and minimal mathematics. It really doesn't matter that the phenomenon of light cannot be neatly placed in one category, because in reality, light is neither a wave nor a particle. The models are used to help simplify the explanation of these observations. This story will continue in the next lesson where the atomic models are looked at more closely.

Practice Answers

Check Prior Knowledge

Term	Definition
Ultraviolet	Portion of E&M spectrum above the visible (in frequency)
Infrared	Portion of E&M spectrum below the visible (in frequency)
Wavelength	Inversely proportional to frequency
Opaque	Metals, for example
Transparent	Earth's atmosphere, for example
Solar Eclipse	Shadow of the Moon falls on the Earth
Lunar eclipse	Moon passes into the shadow of the Earth
Umbra	Total shadow
Penumbra	Partial shadow
Cones in the eye	Make color vision possible
Rods in the eye	Make non-color vision possible
Additive primary colors	Red, green and blue

Section 3: The Mirror Equation

a. If the image is located twice as far from the mirror as the object, calculate the focal length as a function of object position. $f = (2/3)d_o$

b. If the image is located twice as far from the mirror as the focal point, calculate the image height as a function of object height. $h_i = -h_o$

c. Where should the object be located so there is no image? The object should be placed at the focal point.

Section 4: Diffraction and Interference

Derive an equation that allows finding the wavelength of the incident light. $\lambda = (wx)/L$