GEOMETRICAL OPTICS

INTRODUCTION

The formation of images in optical instruments can be analyzed by using a few simple rules based on general wave behavior and straightforward geometrical constructions. Most of what you need to know can be learned from a computer tutorial developed by Crosseducational Software. Your instructor will tell you on which computers the optics tutorial is available and how to access it.

When you reach the optics tutorial, the computer will display a menu of topics. You choose a topic by typing the appropriate number. The topics in the main menu and the two submenus relevant to this experiment are:

1. Rules for Ray Diagrams
2. Lens and Mirror Experiment
3. Waves
4. Diffraction
5. Lasers
6. Quit

The first two menus have nearly identical submenus with the following choices (again selected by typing the appropriate number):

1. Introduction [and Image Formation]
2. Concave Mirror
3. Convex Mirror
4. Concave Lens
5. Convex Lens
6. Quiz
7. Exit

The tutorials display instructions on how to proceed. Generally you proceed from one screen to the next by pressing the space bar. If you wish to stop before reaching the normal end point of a menu or submenu, you can press the escape key at any time (you may need to press it several times). When a menu is displayed, you can leave the tutorial by typing the number corresponding to "Exit" or "Quit."

RULES OF GEOMETRICAL OPTICS

The direction in which a light ray travels after reflection from a surface is determined by the simple statement "the angle of reflection equals the angle of incidence." The angles are measured in opposite directions from a line perpendicular (or "normal") to the surface at the point where the light ray strikes the surface. The incident and reflected rays and the normal line all lie in the same plane.

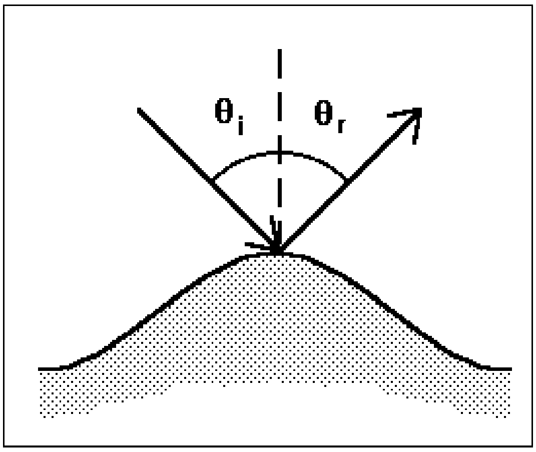

Figure 9.1. Reflection of a light ray from a surface.

The index of refraction of a substance is the ratio of the speed of light in vacuum to the speed of light in the substance. (All light travels at the same speed of 2.998×10^8 m/s in vacuum, but in matter the speed of light in general depends on its frequency, resulting in different indexes of refraction for different colors.) When a light ray passes from one substance into another, its direction changes according to Snell's Law,

$$n_1 \sin \theta_i = n_2 \sin \theta_t \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (9.1)$$

The indexes of refraction of the two substances are n_1 and n_2, and the angles of incidence θ_i and of transmission θ_t are measured from the normal to the surface separating the two substances, as indicated in Figure 9.2 for a case where $n_2 > n_1$.

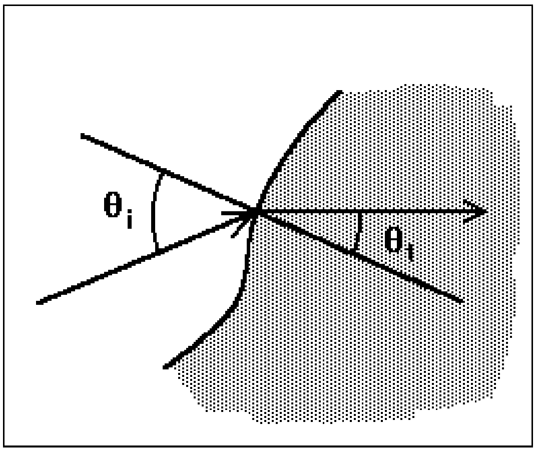

Figure 9.2. Refraction of a light ray at the boundary between two media.

We will consider circular mirrors and lenses with spherical surfaces. The symmetry axis will be referred to as the optic axis. The reflection or refraction of certain light rays by these mirrors and lenses can be described very easily. In particular, light rays which are incident parallel to the optic axis are reflected or refracted in a direction which makes them or their backward extension pass through a point on the optic axis (called the focal point, or simply the focus). The distance f of the focal point from the mirror surface or from the center of the lens is called the focal length. For spherical mirrors, the focal length is half the radius of curvature of the mirror surface. The tutorial illustrates some additional rays whose paths are easy to construct.

Imagine that an object (e.g. a candle) is placed at a distance u from a lens or mirror. All the light rays from a point on the object to the lens or mirror will be refracted or reflected so that they or their backward extensions will pass through a single point, called the image, located at a distance v from the lens or mirror. Only the displacement components parallel to the optic axis are considered in determining the object and image distances. It turns out that there is a very simple relationship between the object and image distances and the focal length:

$$(1 / u) + (1 / v) = (1 / f) \dots\dots\dots\dots\dots\dots (9.2)$$

The transverse displacement components of object and image points are proportional to the displacements parallel to the optic axis. If a plane or linear object is positioned perpendicular to the optic axis, its image will therefore be scaled in size by a factor of

$$M = -(v / u) \dots\dots\dots\dots\dots\dots (9.3)$$

which is called the "magnification," even if it is actually a reduction in size (for $v < u$). The negative sign is used to indicate that the image is inverted (or upside down) compared to the object.

If a focus or an image is located on the same side of a mirror or on the opposite side of a lens as the incident light, the reflected or refracted light rays actually pass through a common point, and the image is said to be real. If a focus or an image is located on the opposite side of a mirror or on the same side of a lens as the incident light, the backward extensions of the reflected or refracted light rays pass through a common point, but the actual rays do not. This results in a virtual image. In order for Equation (9.2) to be correct in these cases, f or v is given a negative sign (with the absolute value still equal to the distance from the lens or mirror). Virtual images are not inverted, and this is indicated by a positive magnification when a negative image distance is inserted into Equation (9.3).

More complex optical instruments can be designed by having a series of lenses and mirrors. The image of the first component is the object for the second component, etc. In this case it is also possible to have a negative object distance, if the image formed by an optical component is located beyond rather than ahead of the next component.

PROCEDURES

Study the "Rules for Ray Diagrams" and "Lens and Mirror Experiment" tutorials. Move the candle back and forth in front of each type of lens and mirror. List the characteristics of the images when the object is located in the following regions or at the following points:

$u < 2f$ $\qquad f < u < 2f$ $\qquad u < f$

$u = f$ $\qquad u = 2f$

There are eight possible combinations of image properties:

{real or virtual} and {erect or inverted} and {reduced or magnified}

List all possible ways in which each combination of properties can be achieved, e.g. "convex lens with $u > 2f$" is one way to obtain a real, inverted, reduced image. Also try to think of at least one example of an application for each case, e.g. the human eye for the case just cited.

Make a careful scale drawing showing the object (conventionally an arrow), intermediate images, and final image for an "instrument" consisting of two or more optical components, showing at least two rays from object to image in the manner of the tutorials. Possible examples are the use of a concave lens in front of the convex lens of a human eye in order to correct for nearsightedness, or the use of two or three convex lenses in order to obtain greater magnification in a microscope.

Name:____

Section:____

Partners:____

Geometrical Optics

Properties of Lenses and Mirrors

The table below (with one sample entry) allows you to summarize the images formed by various optical components. Fill in the table, using the definition introduced in the lab manual and the following abbreviations:

u = object distance	v = image distance	f = focal length
R = real	E = erect	M = magnified
V = virtual	I = inverted	S = reduced (smaller)

Image properties for different optical devices.

Device	$u < f$	$f < u < 2f$	$u > 2f$
Concave Mirror	______________	______________	______________
Convex Mirror	______________	______________	______________
Concave Lens	______________	______________	______________
Convex Lens	______________	______________	*R, I, S*

Correction for Nearsightedness.

On the drawing, construct the image formed by the single converging lens in the top figure. The focal distance of the lens is indicated by the short vertical line near the right end of the optic axis.

Then construct the image formed by the diverging lens in the lower figure. The focal distance of the new lens is indicated by the short vertical line near the left end of the optic axis.

Using the image formed by the diverging lens as object for the converging lens, construct the final image produced by the two lenses combined on the same diagram. If the converging lens were the lens in a patient's eye, do your drawings suggest why the condition being treated by the prescription of a diverging lens is called nearsightedness?

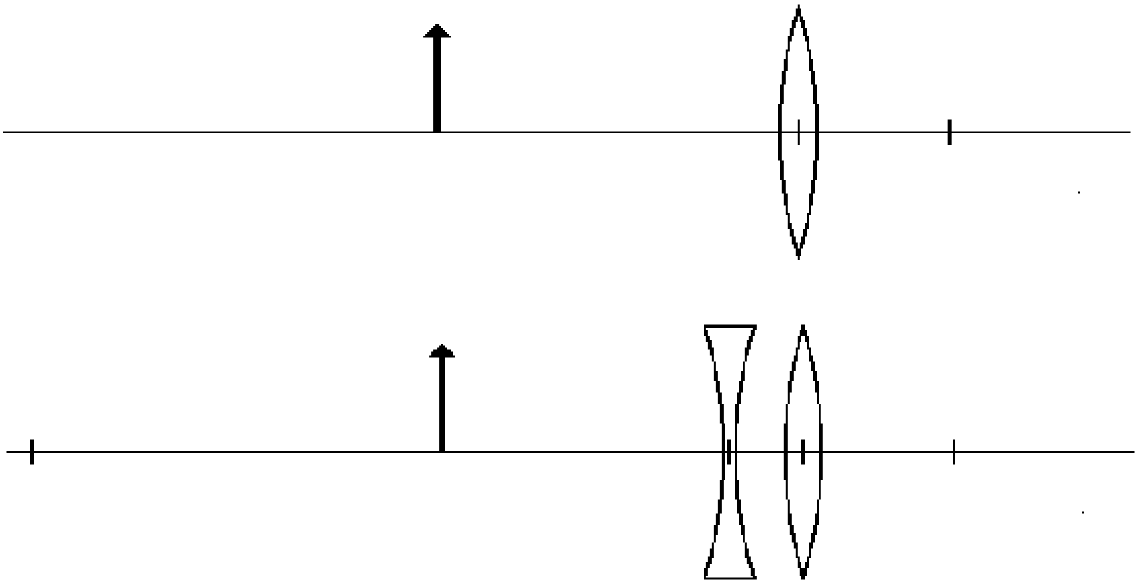

Figure 9.3. Correction for nearsightedness.

Image produced by a combination of optical devices.

If you have time, construct the image formed by another “optical instrument,” which is to say by a combination of two or more optical devices (lenses or mirrors). Make a careful graphical construction of the image produced by the first device. This image then acts as the object of the second device, and so on.