Experiment 2: Imaging with mirrors and lenses

1 Spherical mirrors

Spherical mirrors are reflective optical components that are used for imaging and beam manipulation. For a given spherical mirror of radius R, the location of the object and the image are related by Equations (1.2-3) and (1.2-4) in the paraxial approximation.

Measure the focal length of the concave spherical mirror. Use the incandescent light source as an object. Place the concave mirror as far from the source as possible so that the object (the filament of the light bulb) can be assumed to be at infinity. Tilt the mirror slightly so that you can locate the focus on a piece of paper.

Verify Equation (1.2-4) for one $z_1 > R$ value of your choice. To make a luminous object, place the diffuser and the crossed arrow target in front of the incandescent light source. Tilt the mirror slightly so that you can locate the image on a piece of paper. Draw a ray diagram explaining image formation and comment on image magnification. Look at your own eye with the concave mirror, first at arm's length, then at a distance of about 1.5 cm. Note the orientation of the image that you see in each case, and draw a ray diagram explaining image formation.

2 Lenses

Lenses are refractive optical components used for imaging and beam manipulation. A *simple* lens consists of two refracting surfaces. (A lens with more than two refracting surfaces is called a *compound lens*.) The exact shape of the surfaces involved depends on the type of lens. The most widely used lenses are *spherical lenses*. These lenses cannot accomplish perfect imaging or beam shaping; they introduce unwanted errors called *aberrations*. However, spherical lenses are very widely used due to the relative technological ease, and hence low cost, with which spherical surfaces can be manufactured. (*Aspherical lenses* or compound lenses are used for more critical applications where aberrations cannot be tolerated.) Simple lenses for which the thickness of the lens can be ignored are called *thin* lenses. Equations (1.2-12) through (1.2-14) in the textbook are valid for simple, thin, spherical lenses.

Lenses can be used in various configurations for imaging purposes. An image may be *erect* (right side up) or *inverted* (up side down) with respect to the object. It may be magnified or demagnified by a certain amount. It can also be a *real image* or a *virtual image*. When light rays converge to a point to create an image, the image is real and can be viewed on a screen (such as a piece of paper). A virtual image is formed when light rays seem to diverge from a point where there are no actual light rays.

Set up an experiment to verify the imaging equation (1.2-13) and magnification (1.2-14) for five values of z_1. To make an object, place the diffuser and the crossed arrow target in front of the incandescent light source. Note that there is a scale on the crossed arrow target to facilitate magnification measurements. (Each tick mark is a millimeter.) Use the $f = 150$ mm lens to image the crossed arrow target. Measure the image distance, orientation, magnification, and type (real or virtual) for object distances of $z_1 > 2f$, $z_1 = 2f$, $2f > z_1 > f$, $z_1 = f$, and $z_1 < f$. For virtual images, you can use the parallax method to locate the position of the image: Look through the lens to see the virtual image. Have your partner hold a pencil right above where you think the virtual image is located. Move your head from side to side and see whether the pencil or the image seems to move more with respect to the background. Whichever seems to move more is closer to you than the other one. Reposition the pencil and repeat until you locate the virtual image. (Magnification measurements for virtual images are more difficult.) Draw a ray diagram explaining image formation for each z_1 value.

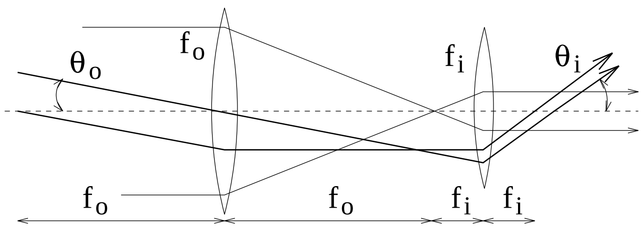
In this experiment, your eye is part of the imaging optics; to "see" an object means having a real image of the object on the retina of your eye. The lens of the human eye is a positive lens that images objects around us onto the retina. To accommodate for different object distances, the curvature and as a result the focal length of the lens changes. For far away objects, the effective focal length is about 17 mm, the distance between the lens and the retina. **Calculate** the focal length that the eye must have to focus onto the retina an object 30 cm away. A nearsighted (myopic) person cannot focus at infinity but can focus on close by objects. What do you think is wrong with his/her lens? A *diopter*, by definition, is one over the focal length in meters; a normal human eye is about 59 diopters. **Calculate** the focal length of the eye of a person who is myopic with a correction of −4 diopters.

3 Stops

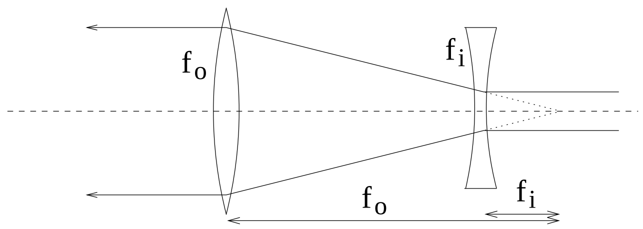
Use the imaging setup in the previous part. Set $z_1 \simeq 2f$. Position an iris between the lens and the object, as close to the lens as possible. Make sure that the iris is centered on the lens. Vary the diameter of the iris and observe the image. In this configuration the iris serves as an *aperture stop*, and works just like the aperture of a camera, controlling the intensity or brightness of the image. Next, position the iris as close to the object as possible and vary the diameter. In this configuration the iris serves as a *field stop*.

4 Telescopes

Telescopes are optical systems used to view far away objects. There are many different types of telescopes. A Keplerian telescope is shown in the figure. Consider an object at infinity with an angular spread of $2\theta_o$. **Show that** the angular magnification $M_\theta \equiv \theta_i/\theta_o$ is $M_\theta = -f_o/f_i$ under the paraxial approximation. **Show that** the transverse magnification, that is the magnification of the transverse size of a parallel bundle of rays, is $M_T = 1/M_\theta$. Construct a Keplerian telescope using the $f = 50$ mm and $f = 150$ mm lenses, and use it to image the crossed arrow target. Focus the image that you see by fine tuning the distance between the two lenses.



Telescopes are also used to manipulate laser beams. A Galilean telescope used for expanding a laser beam is shown in the figure. As in Keplerian telescopes, the distance between the two lenses should be the sum of the focal lengths of the two lenses, with the negative lens having a negative focal length. Similarly, the magnification of the telescope is given by the ratio of the focal lengths. Construct a Galilean telescope using the $f = -25$ mm and $f = 250$ mm lenses to expand the laser beam (diameter approximately 0.48 mm). When constructing a telescope for beam expansion, always verify that the resulting beam is well collimated (the beam diameter stays constant with propagation distance), and adjust the distance between the lenses to achieve this. What is the magnification in the beam diameter?



5 Aberrations

In this part of the experiment you will observe various types of lens aberrations.

1. *Spherical aberration*
   Produce a collimated beam of light by expanding the laser beam with the Galilean telescope of the previous part. Position an iris and the $f = 35$ mm lens in the beam path, as close to each other as possible, with the iris facing the light source. Close the iris down. Find the paraxial focus where a very small light spot is obtained; place a screen at the paraxial focus. Slowly open the iris and observe how the light rays begin to miss the paraxial focus, forming a much broader circle. Translate the screen to find the smallest possible light spot, known as the *circle of least confusion*. Note the relative positions of the circle of least confusion and the paraxial focus.

2. *Coma*
   With the same setup, close the iris down and tilt the $f = 35$ mm lens on the bench by about 20°–30°; you may have to recenter the lens on the beam path. Place a screen at the paraxial focus. Slowly open the iris and observe how the light rays begin to form a shape similar to a comet tail (hence the name coma).

3. *Astigmatism*
   Astigmatism appears when extended off-axis objects are imaged with spherical lenses. To make an object, place the diffuser and the crossed arrow target in front of the incandescent light source. Position the $f = 150$ mm lens 30–40 cm from the object, tilted at angle of about 45°. Note the relative positions of the screen where the vertical and horizontal features of the object come into focus.

4. *Field curvature*
   When flat objects are imaged with spherical lenses, all transverse points on the image are in focus at the same time on a curved surface, instead of a flat plane. (This is why in cinemas with good projection systems, the screen is curved rather than flat.) Position the $f = 35$ mm lens so that image magnification is greater than unity. (Do not tilt the lens.) Concentrate on the millimeter tick marks on the image. The one in the center is not in perfect focus when the ones on the sides are, and vice versa. Describe the curvature of the image field.

5. *Distortion*
   Distortion results when image magnification is a function of radial distance. Look at various images of parallel lines on a piece of paper with the $f = 50$ mm lens. Hold the lens at various distances from the paper, creating both virtual and real images. The two types of distortion that you see are called barrel and pin-cushion due to their shapes. Note your observations.

6. *Chromatic aberration*
   Chromatic aberrations are due to dispersion (wavelength dependent refractive index) in the glass of the lens, resulting in different wavelengths coming to a focus at slightly different distances. Position the diffuser and the 0.75 mm light source aperture in front of the incandescent light source. Image the aperture with the $f = 100$ mm lens so that image magnification is approximately unity. Move the screen back and forth around the focus and observe the colors which appear on the periphery of the image. How does the focal length vary as a function of wavelength?