Reflection

1 Objectives

1. To understand reflection in optical systems, and
2. To determine quantitatively the parameters of various curved mirrors.

2 Introduction

Reflection may well be the first optical phenomenon observed and understood by our evolutionary ancestors. Today it is known that the great apes and a handful of other mammals are able to recognize themselves in their reflections from mirrors and other reflective surfaces, such as water. In this lab, you will test the properties of flat and curved reflective surfaces to confirm the basic soundness of the ray optics limit of our theory of light.

3 Theory

In this lab, we will work in the limit of ray optics - that is, where the feature size of objects we illuminate is much larger than the wavelength of the light. In this limit, we can treat the interfaces between different materials as perfectly smooth surfaces. At those surfaces, light changes direction, or *reflects* from the surface. The relationship between the angle of the incident ray and the angle of the reflected ray can be predicted using *Huygen's Princple*:[1]

> All points on a given wave front are taken as point soures for the production of spherical secondary waves - wavelets - that propagate outward. After some time interval has passes, the new position of the wave front is the surface tangent to the wavelets.

Figure 1 shows rays incident on a surface, along with a wavefront. In the figure, rays 1 and 2 are parallel, and propagate to points A and B, arriving at the same time (the definition of a wavefront). In the time interval δt, ray 1 reflects from the surface and propagates to point D, while ray 2 reaches point C in the same interval. Since both rays travel in the same material during δt, they must travel the same distance: $AD = BC$. Now[2] at the point of reflection, each ray will generate a spherical wavelet; at any later time, those expanding wavelets will,

[1] Serway and Jewett, *Physics for Scientists and Engineers*, 8th Ed.

[2] And this is the key point, one which the Serway and Jewett text inexplicably leaves out!

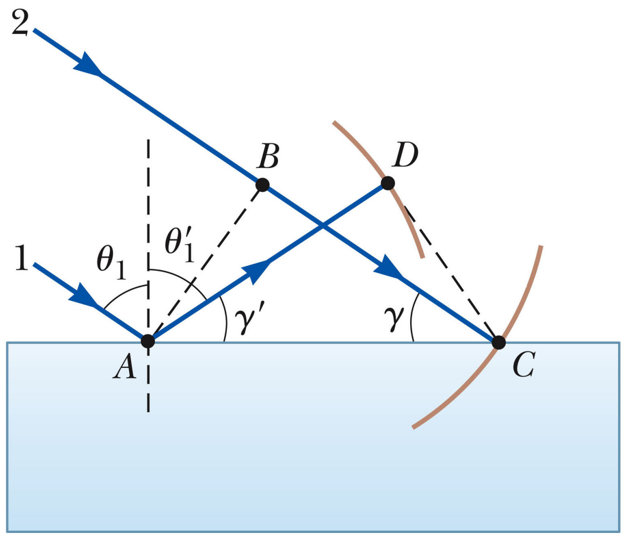

Figure 1: The Incident and reflected rays discussed in the text.

by symmetry, construct a wavefront that is normal to the direction of propagation. Since the wavefront passed through AB at the earlier time, it must pass through CD at the later instant, so the wavefront must be perpendicular to the ray AD! Geometrically, then, the two triangles DAC and BCA are congruent, and $\gamma = \gamma'$. Therefore the incident and reflected angles must be equal:

$$\theta_I = \theta_R \ .$$

Additionally, the incident and reflected rays are coplanar with the normal at the point of incidence, and the incident and reflected waves always lie on opposite sides of the normal. This type of reflection from an ideal, smooth surface is called *specular* reflection, as opposed to the *diffuse* reflection off a rough surface.

If we curve the mirrors, the seemingly simple relation gives rise to a rich set of phenomena, which have a close relationship to the behavior of thin lenses. Just like lenses, mirrors can be used to focus images of objects, and those images will be scaled copies of the objects; see Figure 2. We focus here on the behavior of mirrors that are circular or spherical sections; other types of mirrors (parabolic, hyperbolic, etc) exist, but they have significantly more complicated properties than what we will discuss here.

Describing the behavior of spherical mirrors quantitatively requires a few definitions. First, define the *principal axis* as a ray that runs through the center of curvature (the center of the circle that the mirror lies on) and the center of the circular mirror section. Next, put the base of the object on the principal ray. Define the distance along the principal ray from the object to the mirror as p, and the distance from the image to the mirror as q.. The object and image may be either *real* - if rays actually travel the distance to the mirror - or *virtual* - if the rays do not actually travel the distance to the mirror. These distances are related to the curvature of the mirror by

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f} \ .$$

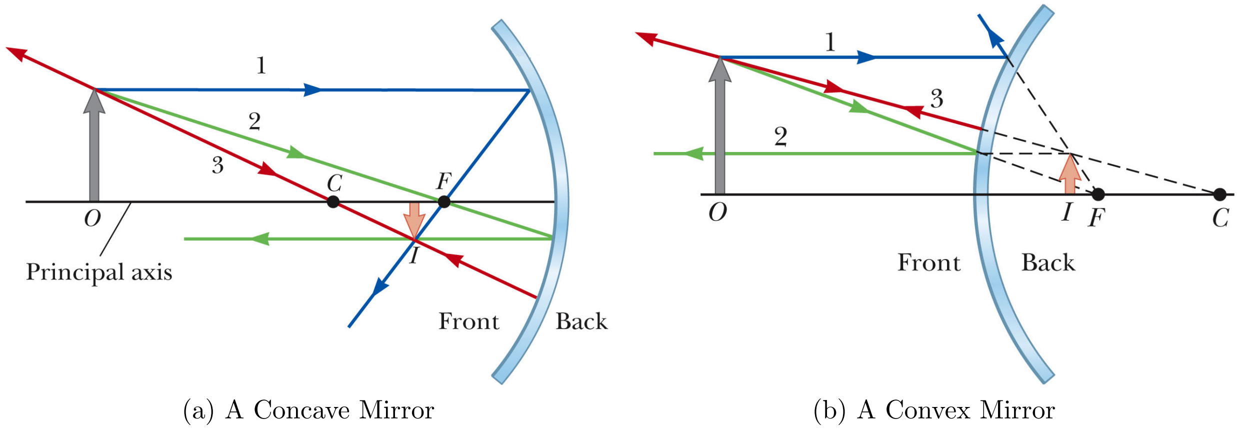

Figure 2: These figures illustrate the ray diagram construction for determining the image position and magnification, as described in the text.

The focal length, f, of the mirror is simply half the radius of curvature r of the mirror

$$f = \frac{r}{2} \ .$$

When the object or image are real, the distance is taken (by convention) as positive; if virtual, the distance is taken as negative. You can prove that the focal length of a concave mirror is positive, while the focal length of a convex mirror is negative.

The image and object distances also give the image magnification, which is the ratio of the image height h_i to the object height h_o:

$$M = \frac{h_i}{h_o} = -\frac{q}{p} \ ,$$

where a negative magnification corresponds to an image *inverted* with respect to the object orientation.

We can graphically illustrate the properties of a curved mirror by constructing *ray diagrams*. For a concave mirror, draw three rays from the top of the object (the base, of course, lies on the principal axis):

1. Ray 1, parallel to the principal axis to an intersection with the mirror. The reflected ray will pass through the focal point.

2. Ray 2, through the focal point. The reflected ray will be parallel to the principal axis.

3. Ray 3, through the center of curvature. Since this is normal to the surface (it's along a radius) this will be reflected back on itself.

The intersection point of these three rays (real or virtual) defines the image. For a convex mirror, since the focus and center of curvature lie on the *other* side of the mirror from the object, the construction varies slightly; determine the modifications by reference to Figure 2. To find the focal point, we utilize a set of rays all parallel to the principal axis; this is equivalent to having an object at infinity, and the image then appears with zero height *at* the focal point.

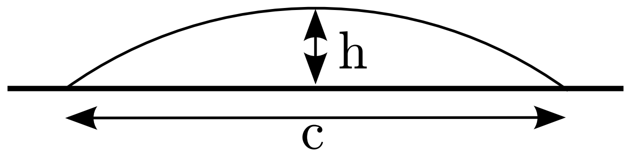

Figure 3: The radius of curvature of a circular segment can be determined if the chord length, c, and the height, h, of the segment are known.

4 Procedures

You should receive a laser pointer, a set of flat and curved mirrors, sheets of white paper, rulers and protractors.

4.1 Flat Mirrors

Using your flat mirror, perform ray tracing for a number of incident angles (say, 5). Measure the reflected angles to confirm or refute the equality of θ_I and θ_R. What is your largest source of uncertainty?

4.2 Curved Mirrors

For both the concave and convex mirrors, determine the focal lengths by the parallel ray construction method, and compare this to the focal length determined from the radius of curvature. Assuming the mirror is a segment of a circle, you can determine the radius of curvature r by measuring the chord c and the height h of the segment:

$$r = \frac{h^2 + (c/2)^2}{2h} \;;$$

the variables are defined in Figure 3. The radius is positive for concave mirror, and negative for a convex mirror.

Now that you have determined the focal length, use your lasers to recreate the image construction outlined in Figure 2. There are three cases you should consider: for the convex mirror, find the location and size of the virtual image; for the concave mirror, determine the location and size of the images for objects that are closer to and further from the mirror than the focal point. For all three cases, measure p and q, as well as the transverse heights of the objects and images.

Pre-Lab Exercises

Answer these questions as instructed on Blackboard; make sure to submit them before your lab session!

1. The focal length of a convex mirror is negative. What does this tell you about the size of the magnification of the image? The sign?
2. For a concave mirror, an object is place three focal lengths from the mirror. Where is the image? What is its orientation?
3. Does a flat mirror produce a real or virtual image? What is its magnification?

Post-Lab Exercises

1. Does your data from Section 4.1 support the Huygen's Construction where $\theta_I = \theta_R$? Discuss your uncertainties.

2. From your data in Section 4.2, what are the focal lengths and radii of curvature for your two mirrors? Discuss your uncertaintites. Are the mirrors circular? How do you know?

3. From your data in Section 4.2, do the predicted magnifications match the measured magnifications? Discuss your uncertainties.

4. Discuss briefly whether you have met the objectives of the lab exercises.