General Physics II Lab (PHYS-2021)
Experiment OPTC-1:
Mirrors, Lenses and Image Formation

Introduction - Mirrors:

A *spherical mirror* is a section of a spherical surface of radius R. There are two types of spherical mirrors as shown in Figure 1:

- **Concave mirror**: Reflecting surface is on the "inside" of the curved surface.
- **Convex mirror**: Reflecting surface is on the "outside" of the curved surface.

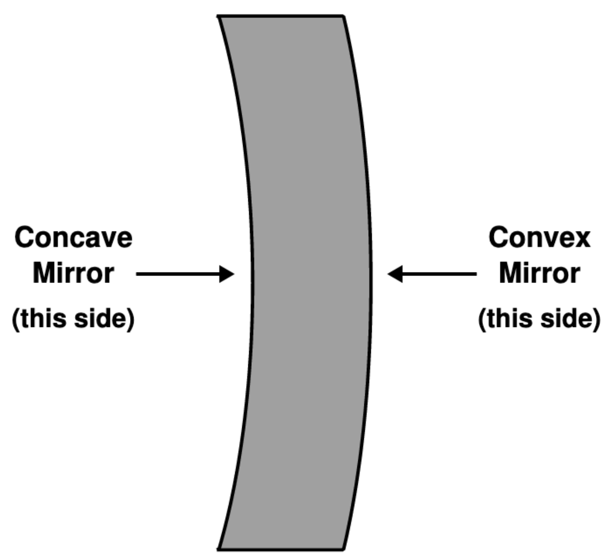


Figure 1: Two types of spherical mirrors.

Spherical mirrors may be used to form images from an *object* in the field of view of the mirror. In this laboratory experiment, you will learn how to construct an image for spherical mirrors using two different methods:

1. **Analytic method**: One uses algebra and trigonometry, making use of the *mirror equation* and the *thin mirror equation*, to determine the location, orientation, and size of an image.

2. **Experimental method**: One uses mirrors, a source, and an image screen on an optics bench to determine the focal length (or radii of curvature) of the mirror. We will only deal with **concave mirrors** for the experimental method.

When dealing with image formation from mirrors, there are a variety of terms that we must define first.

- Image orientation:
  - **Erect Image**: Image is oriented the same as the object.
  - **Inverted Image**: Image is flipped 180° with respect to the object.
- Image classification:
  - **Real Image**: Image is on the same side of mirror as the object
    $\longrightarrow$ light rays actually pass through the image point.
  - **Virtual Image**: Image is on the opposite side of mirror from object
    $\Longrightarrow$ light rays appear to diverge from image point.
- Image size is determined by the magnification of an object which is given by

$$M \equiv \frac{\text{image height}}{\text{object height}} = \frac{h'}{h} \tag{1}$$

$\lvert M\rvert > 1$	$\Longrightarrow$	Image is bigger than object (magnified).
$\lvert M\rvert = 1$	$\Longrightarrow$	Image is unmagnified (like a plane mirror).
$\lvert M\rvert < 1$	$\Longrightarrow$	Image is smaller than object (de-magnified).
$M > 0$	$\Longrightarrow$	Image is erect.
$M < 0$	$\Longrightarrow$	Image is inverted.
$M = 0$	$\Longrightarrow$	No image is formed.

In the box above, |M| means the absolute value of the magnification M.

Image Formation with Concave Mirrors

Figure 2 shows a drawing of a concave mirror with various defining labels/markers of the mirror and an example of image formation for these mirrors.

- The line that is normal to the mirror surface at the exact center is called the **optical axis** of the mirror.
- The point where the optical axis intersects the mirror surface is called the **vertex**.

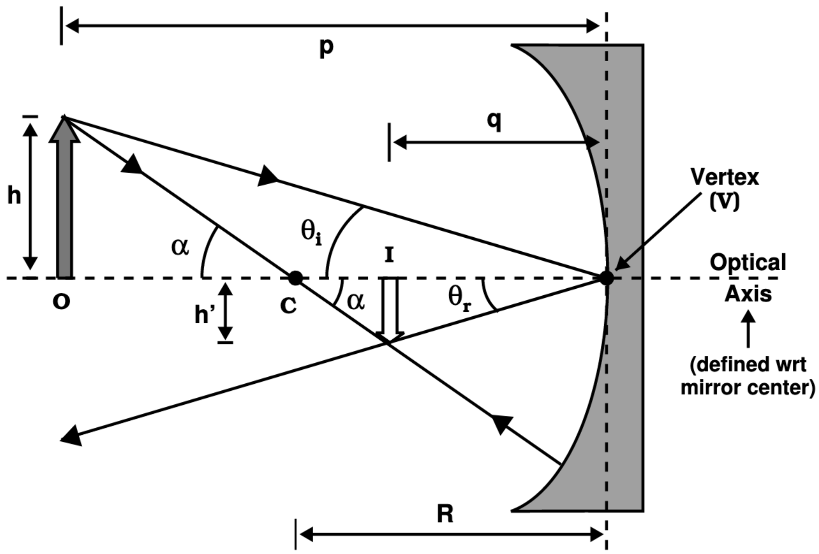


Figure 2: Image Formation Example for a Concave Mirror.

- Point 'C' indicates the position of the **center of curvature** of the mirror
$\Longrightarrow$ line CV is equal to the **radius of curvature**, R, of the mirror.

- The **object** is labeled with 'O' and is designated with a 'filled' arrow in Figure 2. It is located at a distance p from the vertex on the optical axis of the mirror and has a height of h.

- The **image** is labeled with 'I' and is designated with a 'unfilled' arrow in Figure 2. It is located at a distance q from the vertex on the optical axis of the mirror and has a height of h'.

- Follow the principle ray from the tip of the object down to the vertex V. The angle that ray makes with the optical axis we will label as θ_i, where 'i' means 'incident' angle.

- That ray then gets reflected from the mirror at the vertex using the law of reflection. The angle between the reflected ray and the optical axis will be labeled as θ_r, where the 'r' means 'reflected' angle.

- To construct the image from that object, we use the law of reflection:

$$\theta_i = -\theta_r, \tag{2}$$

where θ is measured with respect to the normal of the mirror surface at the vertex V. The 'negative' sign is introduced here to note that the reflected angle sweeps away from the optical axis in the opposite 'sense' of the incident angle.

- All normal lines on spherical concave mirrors go through the center of curvature point C ($\theta_i = \theta_r = 0$)!

- Now look at the triangle involving sides h, p, and angle θ_i, and the triangle involving sides h', q, and angle θ_r in Figure 2. Using trigonometry, we see that

$$\frac{h'}{q} = tan\ \theta_r \quad \& \quad \frac{h}{p} = tan\ \theta_i.$$

  - Since θ_i = -θ_r, we get tan θ_i = -tan θ_r, and hence

$$\frac{h'}{q} = -\ tan\ \theta_i = -\frac{h}{p} \quad or$$

$$M = \frac{h'}{h} = -\frac{q}{p} \tag{3}$$

  - The magnification also can be determined by the ratio of the image to the object distance.

Finally, using the similar α triangles in Figure 2 and Equation (3) we have:

$$\frac{1}{p} + \frac{1}{q} = \frac{2}{R} \tag{4}$$

which is the **mirror equation** for spherical mirrors.

  - When $p \gg R$, the object is very far from the mirror and 1/p $\approx$ 0 approaching infinity and the incoming rays are essentially parallel because the source is assumed to be very far from the mirror so we can say the focal length of the mirror is

$$f = \frac{R}{2} \tag{5}$$

  - Therefore Eq. (4) can be rewritten as

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f} \tag{6}$$

- Both convex and concave mirrors use Eq. (6), except there is a “change“ in sign for the radius and focal length of the mirror. Table 1 shows the sign conventions used for the geometric optics parameters for curved mirrors.

Table 1: Sign Conventions for Curved Mirrors

	PLUS (+)	**MINUS (-)**
p	object left of mirror (real object)	object right of mirror (virtual object)
q	image same side of mirror as object (real image)	image opposite side of mirror as object (virtual image)
h	object is erect	object is inverted
h'	image is erect	image is inverted
M	image is in same orientation as object	image is inverted with respect to object
R	concave mirror	convex mirror
f	concave mirror	convex mirror
symbol	$\overset{light}{\longrightarrow}$)	$\overset{light}{\longrightarrow}$ (

- Image location can either be determined algebraically from Eqs. (3) & (6), by drawing ray diagrams, or by experimental methods. For the Ray diagram method, there are **three principle rays** that define the image location for **concave mirrors** as shown in Figures 3:

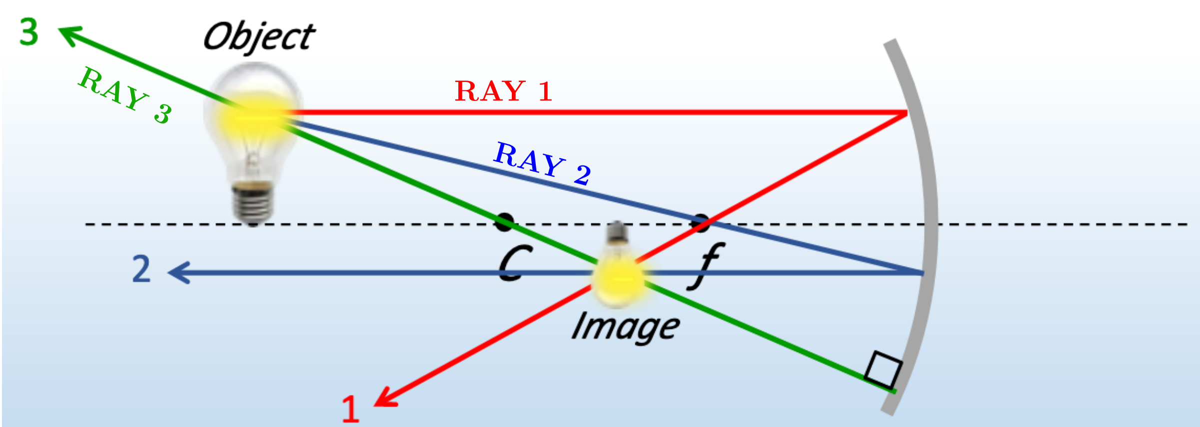


Figure 3: Three Principle Rays of a Concave Mirror

  - Ray 1 is parallel to the optical axis and reflected back through the focal point, F.
  - Ray 2 goes through the focal point, F, and reflected parallel to the optical axis.
  - Ray 3 goes through the center of curvature, C, and reflected back on itself.

Image Formation with Convex Mirrors

The equations that we developed for concave mirrors are also valid for convex mirrors except the signs for the various parameters are opposite of what they were for concave mirrors as shown in Table 1. Just as we had for concave mirrors, we can define **three principle rays for convex mirrors** as shown in Figure 4:

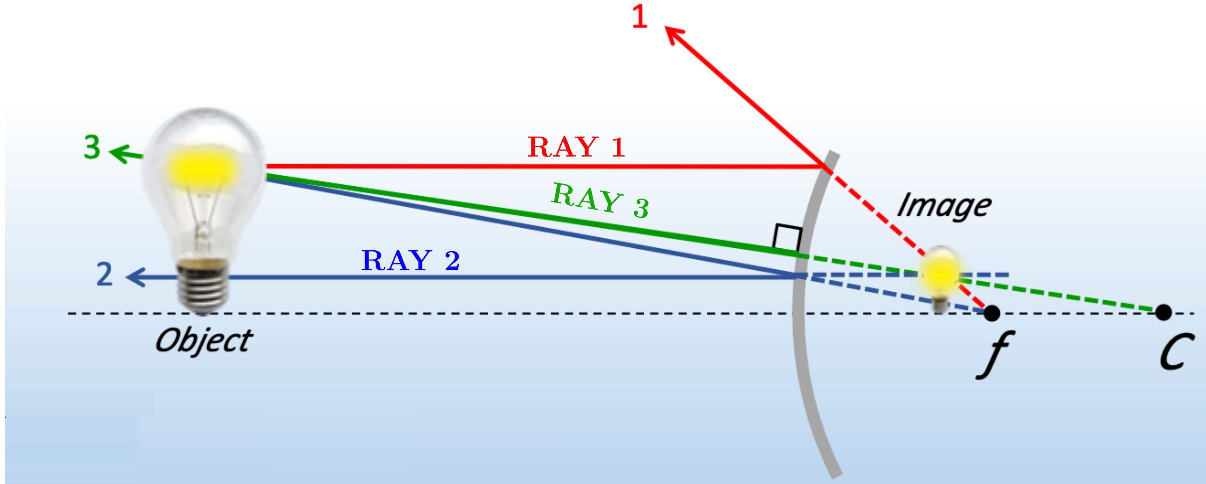


Figure 4: Three Principle Rays of a Convex Mirror

- Ray 1 is parallel to the optical axis and reflected back through the focal point, F.
- Ray 2 goes through the focal point, F, and reflected parallel to the optical axis.
- Ray 3 goes through the center of curvature, C, and reflected back through C.

Introduction - Lenses:

When light travels from one medium to another, part of the light can be **transmitted** across the media surface and **refracted** as shown in Figure 5.

- **Refraction** means that the light beam changes directions.
- This change takes place because the light beam's (*i.e.*, photon's) velocity changes as it goes from one medium to the next, following the relation:

$$\frac{sin\ \theta_r}{sin\ \theta_i} = \frac{v_r}{v_i} = \text{constant.} \tag{7}$$

  - v_r and θ_r are the velocity and the angle of the refracted beam with respect to the normal line of the surface
  - v_i and θ_i are the velocity and the angle of the incident beam with respect to the normal line of the surface

The **index of refraction**, n, of a material is defined as

$$n \equiv \frac{\text{speed of light in vacuum}}{\text{speed of light in medium}} = \frac{c}{v} \tag{8}$$

Eq. (7) can be re-expressed as a function of $n \Longrightarrow$ **Law of Refraction** better known as **Snell's Law**:

$$n_1\ sin\ \theta_1 = n_2\ sin\ \theta_2 \tag{9}$$

where the label '1' indicates the first medium the light is in and the '2' label indicates the second medium (see Figure 5).

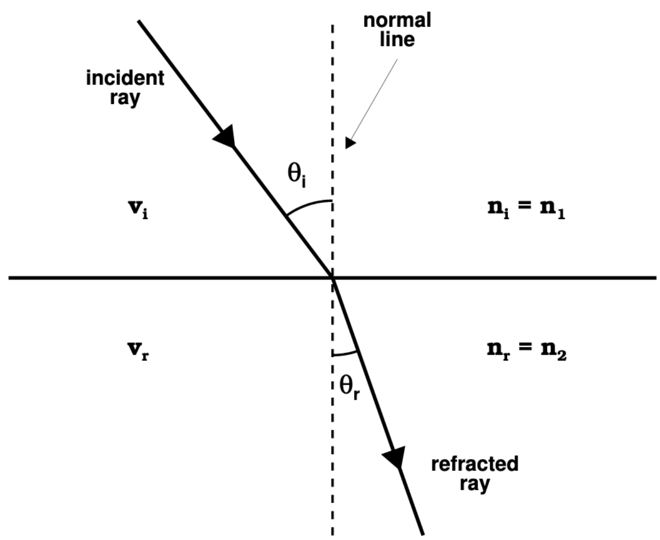


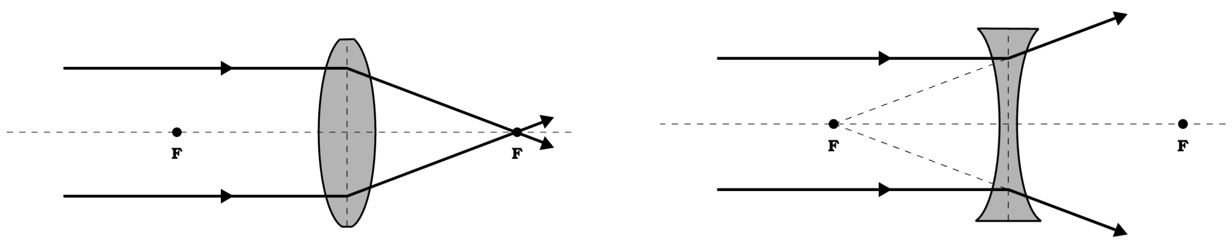
Figure 5: Snell's Law: The Law of Refraction

In Part B of todays lab, you will carry out experiments with lenses and how they form images. This experiment will involve placing lenses and sources on an optical bench along with an image screen to determine the focal length of both converging and diverging lenses. A **converging lens** is thicker at its center than at its edges (see Figure 6a), where as a **diverging lens** is thinner at its center than at its edges (see Figure 6b). For a converging lens, light rays are refracted towards the focal point, F, on the other side of the lens. Meanwhile for a diverging lens, light rays are refracted in a direction away from the focal point, F, on the near side of the lens.

Image Formation with Thin Lenses

Just as we had for mirrors, we will make use of the *simple lens / mirror equation*:

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f} \tag{10}$$



(a) A Converging Lens

(b) A Diverging Lens

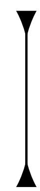
Figure 6: Thin Lenses

where p is the object distance from the mirror, q is the image distance, the focal length is f. Like we had for the mirrors, the magnification of the image is given by Equation 12.

$$M \equiv \frac{\text{image height}}{\text{object height}} = \frac{h'}{h} = -\frac{q}{p} \tag{11}$$

The sign convention for lenses are the same as for mirrors except for q, when $q > 0$ the image is on the opposite side of the lens and when $q < 0$ the image is on the same side of the lens as the object (see Table 2).

Table 2: Sign Conventions for Thin Lenses

	PLUS (+)	**MINUS (-)**
p	object in front of lens (real object)	object in back of lens (virtual object)
q	image in back of lens (real image)	image in front of lens (virtual image)
h	object is erect	object is inverted
h'	image is erect	image is inverted
M	image is in same orientation as object	image is inverted with respect to object
R	center of curvature in back of lens	center of curvature in front of lens
f	converging lens	diverging lens
symbol		

Ray Tracing Rules for Thin Lenses

- The first ray (*i.e.*, Ray 1) is drawn parallel to the optical axis from the top of the object. After being refracted by the lens, this ray either passes through the focal point, F, on the other side of the lens (for a converging lens), or appears to come from the nearside focal point, F, in front of the lens (for a diverging lens).

- The second ray (*i.e.*, Ray 2) is drawn from the top of the object and through the center of the lens. This ray continues on the other side of the lens as a straight line.

- The third ray (*i.e.*, Ray 3) is drawn through the focal point, F, on the nearside for converging lenses and emerges from the lens on the opposite side, parallel to the optical axis. For diverging lenses, one draws Ray 3 starting from the top of the object and projects it to the focal point on the far side of the lens. When this ray passes through the lens, this ray comes out parallel to the optical axis as shown in the bottom figure of Figure 7.

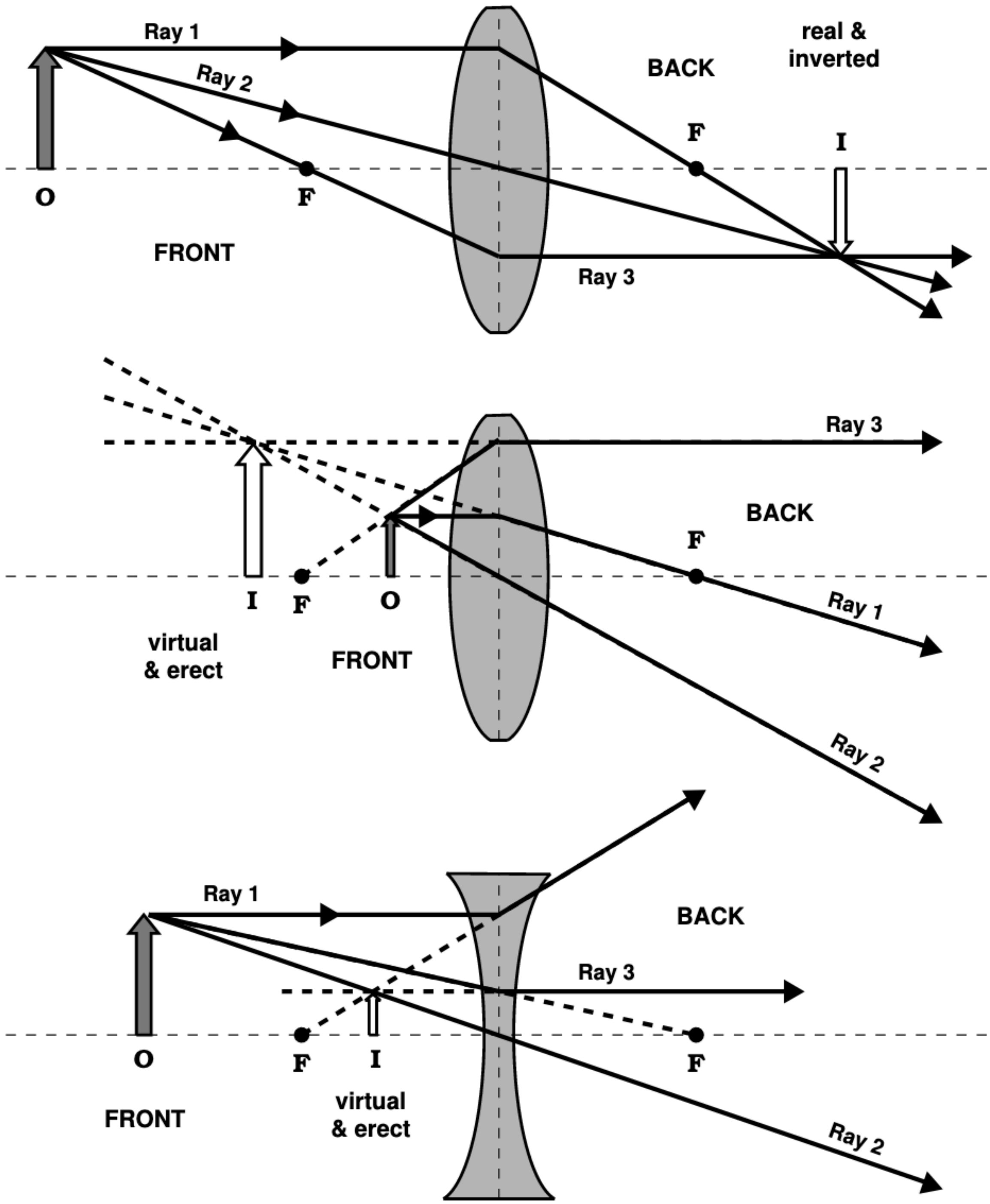


Figure 7: Ray Tracing Rules for Thin Lenses.

Mirrors Experimental Setup:

The Concave/convex Mirror Accessory is designed for use with a PASCO optics bench (OS-8508). It consists of a double sided curved mirror (OS-8457) and a semicircular half-screen (OS-8457). The mirror is concave on one side and convex on the other side. We will only be working with the concave side in the experimental portion of this lab. Both sides have the same radius of curvature. See Figure 8 for a drawing of the experimental set-up for this lab.

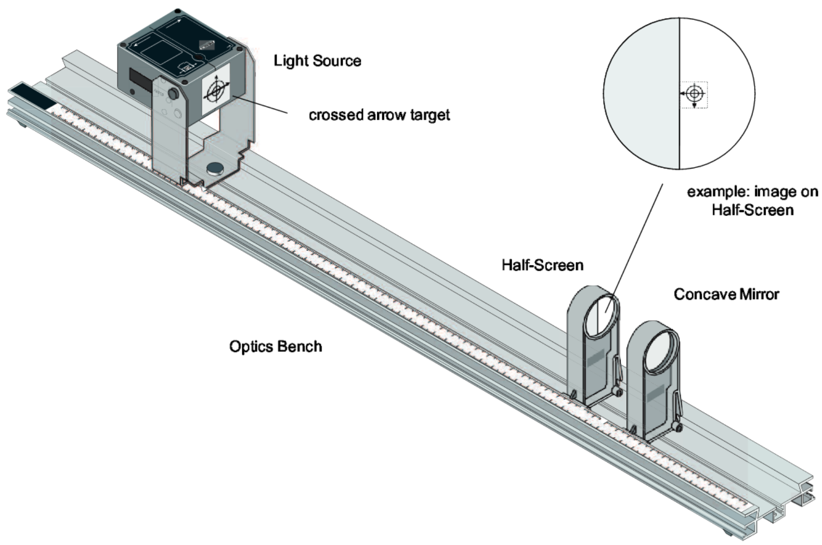


Figure 8: Experimental set-up for the concave spherical mirror experiment.

The half-screen is designed for showing an image formed by the concave side of the mirror. The screen on the half-screen can be rotated in its mount so that its edge is vertical or horizontal as shown in Figure 9.

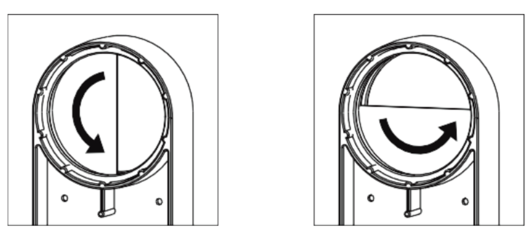


Figure 9: Two possible orientations for the half-screen.

The concave mirror accessory and the half-screen accessory snap into place on the Optics Bench. To move an accessory along the bench, grasp the base of the accessory holder and squeeze the locking clip inward. Continue to squeeze inward on the locking clip as you move the accessory to the new position. When you release the locking clip, the accessory holder is held firmly in place.

Procedure Part A - Mirrors

In this part of the lab, we will only be working with **concave mirrors**. The purpose of this experiment is to measure the focal length of a concave mirror.

Experimental Procedure

1. Mount the Light Source at one end of the Optics Bench.
2. Place the Concave Mirror at 25 cm.
3. Position the Light Source so the crossed arrow target on the light source is aimed at the Concave Mirror and the concave surface of the mirror faces the light source.
4. Place the Half-Screen between the mirror and the Light Source.
5. Move the Half-Screen closer to or farther from the Concave Mirror until the reflected image of the crossed arrow target on the white screen is focused.
6. Measure the distance between the crossed-arrow object slide on the light source and the position indicator on the Concave Mirror – this will be your object distance, p.
7. Measure the distance between the position indicators on the Half-Screen and the Concave Mirror – this will be your image distance, q.
8. Measure the height of white light square, h on the crossed-arrow object slide on the Light Source box and the size of the image, h' on the half-screen using your metric ruler. Do the best you can when measuring the image size on the half-screen.
9. Repeat steps 4-8 with mirror at 35cm and 45cm.
10. Record p, q, h, h' for each distance in Table 3.
11. Calculate the focal length of the mirror using Eq. (6).
12. Calculate the magnification of the image using the ratio of h' over h in Eq. (3),
13. Calculate the magnification of the image using the negative ratio of q and p in this equation.
14. Record answers in Table 3. ***Reminder: Use the correct sign conventions in Table 1.***
15. For each trial, compare your experimental f_{avg} value to the stated focal length value of $f_{theoretical} = 10.0$ (cm) using Equation 12.
16. Record answers in Table 3.

Procedure Part B - Lenses

For the experimental portion of this part of the lab, there are 3 lenses labeled: L1 (a converging lens of focal length $f_1 \approx 10$ cm), L_2 (a converging lens of focal length $f_2 \approx 20$ cm), and L_3 (a diverging lens of focal length $f_3 \approx$ -15 cm).

1. Set up a real image configuration on the optical bench using the **converging lenses** L_1 and L_2.
2. Measure p and q.
3. Calculate f for each lens as described below.
4. A typical real-image configuration is shown in Figure 10 below.

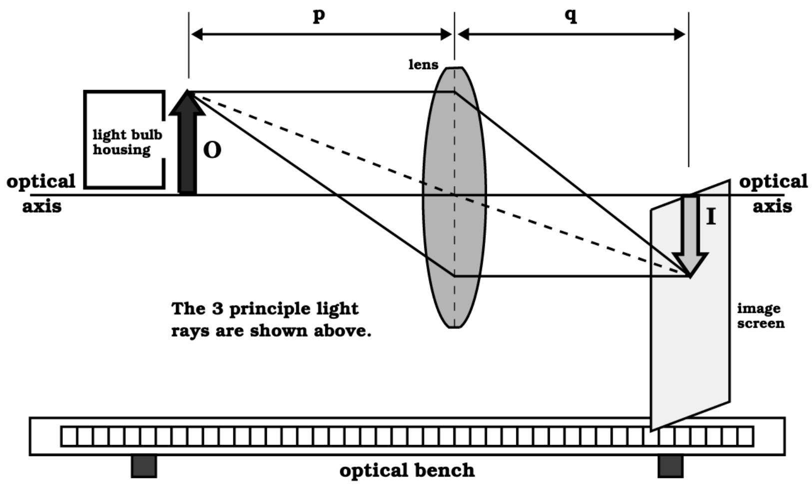


Figure 10: Converging lens real-image configuration on the optical bench.

(a) Find the focal length, f_1, of lens L_1 as follows:

i. Place the object slide, O, on the optical bench at the 0.0 cm position.
ii. Place the image screen at the 50.0 cm position.
iii. Mount L_1 on the optical bench *between* O and the screen.
iv. Locate the two positions where a sharp image, I, is formed on the screen.
v. One of these positions will be about 10–12 cm from the object slide and the other about 10–12 cm from the screen.
vi. Measure and Record (in cm) the object distance p and the image distance q for each of the positions of L_1.
vii. Calculate the focal length f_1 using the simple lens/mirror equation (Eq. 10).
viii. Record p, q, f_1 in Table 4.

(b) Find the focal length, f_2, of lens L_2 as follows:

   i. Place the object slide, O, on the optical bench at the 0.0 cm position.
   ii. Place the image screen at the 110.0 cm position.
   iii. Mount L_2 on the optical bench between O and the screen and locate the two positions where a sharp image, I, is formed on the screen.
   iv. One of these positions will be about 20-25 cm from the object slide and the other about 20-25 cm from the screen.
   v. Measure and Record (in cm) the object distance p and the image distance q for each of the positions of L_2.
   vi. Calculate the focal length f_2 using the simple lens/mirror equation (Eq. 11).
   vii. Record p, q, f_2 in Table 5.

5. Set up a *two-lens* configuration on the optical bench as follows:

   (a) Place the object slide, O, at the 0.0 cm position, L_1 at 11.0 cm, and L_2 at 35.0 cm.
   (b) Adjust the screen position so that a sharp image is formed.
   (c) Measure and Record the object distance p_1 for L_1, the image distance q_2 for L_2, and the lens separation distance d.
   (d) Record p_1, q_2, d in Table 6.
   (e) Use the simple lens/mirror equation (Eq. 11) to calculate the image distance q_2.
   (f) Use the values for f_1 and f_2 determined in Step 1. Eq. (11) must be used twice – first for L_1 and again for L_2.
   (g) Compare your calculated value for q_2 with that measured on the bench, $q_{measured}$.
   (h) Record answers in Table 6.

6. Determine the focal length of the diverging lens use two lenses, one diverging and the other converging, and follow the technique described in Step 2.

   (a) Place the object slide, O, at the 0.0 cm position, L_1 at 20.0 cm, and the image screen at 60.0 cm.
   (b) Place the diverging lens L_3 on the bench between L_1 and the screen. Now adjust the diverging lens position until you get a sharp image on the screen.
   (c) Measure the object distance p_1 for L_1, the image distance q_3 for L_3, and the lens separation distanced.
   (d) Record answers in Table 7.
   (e) Calculate the focal length f_3 of the diverging lens L_3 using the simple lens/mirror equation (Eq. 11),

Lab Report: Mirrors, Lenses and Image Formation

Name: ______________________ Lab Section: __________

Mirrors Questions

1. How does the measured distance compare to the focal length of the Concave Mirror?

2. How might you determine the focal length more accurately?

3. What is the orientation of the image of the crossed arrow target compared to the target itself?

4. How does the size of the image of the crossed arrow target compare to the target itself? Compare your h' and h ratios with your negative q and p ratios. Which of these two ratios is more likely to be the more accurate magnification value and why do you say this?

Analytic Procedure - At Home Exercise

(**Note that this step can be completed at home**.) For each of the following problems, you are to analytically determine the image *location* (supplying proof whether the image is real or virtual), *image size* and *magnification* (supplying proof whether the image is up right or inverted, and magnified or de-magnified). Make sure you pay attention to significant digits for the given input parameters and the results you calculate.

1. An object is 4.30 cm high and is placed 12.6 cm to the left of a concave mirror. The mirror has a radius of curvature of 6.20 cm. Locate and describe the image.

2. An object is 3.60 cm high and is placed 8.20 cm to the left of a concave mirror. The mirror has a radius of curvature of 10.2 cm. Locate and describe the image.

3. An object is 5.50 cm high and is placed 3.30 cm to the left of a convex mirror. The mirror has a radius of curvature of 5.20 cm. Locate and describe the image.

4. An object is 3.62 cm high and placed 12.2 cm in front of a mirror. A real and inverted image of height (-) 2.00 cm is formed. (a) Would a concave or convex mirror be required to form this image? Mathematically prove this answer. (b) What is the radius of curvature of this mirror?

5. Using algebra with the thin-mirror approximation (*i.e.*, Eq. 6), prove that the image produced by a convex mirror is always formed behind the mirror as a virtual image.(Please note that an example is not a sufficient proof!)

6. A 2.00 cm tall object is placed 4.00 cm in front of a concave mirror of radius 8.00 cm. Locate and describe the image.

$$\%_{Error} \;=\; \left(\frac{f_{avg} - f_{theoretical}}{f_{theoretical}}\right) \times\; 100 \tag{12}$$

Table 3: Data and Results - Mirrors

Trial	p	q	h	h'	f	$M = \frac{h'}{h}$	$M =$ - $\frac{q}{p}$	**% Error**
25 (cm)								
35 (cm)								
45 (cm)								

Table 4: Data and Results - Single Lens Part 1

p	q	f_1	f_{avg}	**% Error**

Table 5: Data and Results - Single Lens Part 2

p	q	f_2	L_2

Table 6: Data and Results: Two-Lens Part-1

Measured			**Calculated**	
p_1	q_2	d	q_2	**% Error**

Table 7: Data and Results: Two-Lens Part 2

Measured			**Calculated**	
p_1	q_3	d	q_3	**% Error**

$$\%_{Error} \;=\; \left(\frac{q_{measured} - q_{calculated}}{q_{calculated}}\right) \times\; 100 \tag{13}$$