Lab 10: Spherical Mirrors and Lenses
(Reference: Physics Laboratory Experiments by Jerry D. Wilson)

Objectives:

- To distinguish among converging and diverging spherical mirrors and lenses.
- Determine the image characteristics for spherical mirrors graphically using ray diagrams and analytically using the mirror equation and magnification factor.
- Determine the image characteristics for spherical lenses graphically using ray diagrams and analytically using the thin-lens equation and magnification factor.

Theory:

(A) Spherical Mirrors

A spherical mirror is a section of a sphere and is characterized by a center of curvature C. The distance from the center of the curvature to the vertex of the mirror along the optic axis is called the radius of curvature R. The focal point F is midway between the vertex and C, and the focal length (f) is one half the radius of curvature.

\[ f = \frac{R}{2} \]

If the reflecting surface is on the inside of the spherical section, the mirror is said to be concave. For a convex mirror, the reflecting surface is on the outside of the spherical section.

Images formed by these mirrors can be determined graphically or analytically. We take a look at the graphical method first. There are three important rays and their path needs to be memorized.

1) A ray that is incident parallel to the optic axis will get reflected and must pass through the focal point of the mirror and is called the parallel ray.
2) A ray that is incident and passes through the focal point of the mirror is rendered parallel to the optic axis after reflection and is called the **focal ray**.

3) A ray that is incident and passes through the center of curvature $C$ is reflected back through $C$ and is called the **chief ray**.

The intersection of these rays defines the location of the tip of the **image arrow**, which extends from the optic axis. With these rules in mind we draw the corresponding ray diagrams for a convex and concave mirror below.

A concave mirror is called the **converging mirror** because rays parallel to the optic axis converge at the focal point. Similarly, a convex mirror is called a **diverging mirror** because rays parallel to the optic axis appear to diverge from the focal point.

If the image is formed on the same side of the mirror as the object, the image is said to be a **real image**. In this case, the light rays converge and are concentrated, and an image can be observed on a screen placed at the image distance. An image that is formed “behind” or “inside” the mirror is called a **virtual image**. Here, the rays appear to diverge from the image, and no image can be formed on a screen.

In general, an image is described by the following characteristics:

1) real or virtual
2) upright (erect) or inverted (relative to the object orientation) and
3) magnified or reduced (or smaller).

In Figure 2, the image is real, inverted, and reduced; in Figure 3, the image is virtual, upright and smaller.

![Figure 2: Ray diagrams for concave mirror](image-url)
The distance from the object to the vertex along the optic axis is called the **object distance** \( d_o \), and the distance from the vertex to the image is the **image distance** \( d_i \). Knowing the focal length \( f \) of the mirror, the position of the image \( d_i \) can be found from the **spherical mirror equation**:

\[
\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}
\]

Another convenient form of this equation is:

\[
d_i = \frac{d_o f}{d_o - f}
\]

In the case of a concave mirror, the focal length is taken to be positive (+); for a concave mirror, the focal length is taken to be negative (-). The object distance is taken to be positive in either case. The sign convention is: If \( d_i \) is positive, the image is real; and if \( d_i \) is negative, the image is virtual. The **magnification factor** \( M \) is given by:

\[
M = -\frac{d_i}{d_o}
\]

If \( M \) is positive (\( d_i \) negative), the image is upright; if \( M \) is negative (\( d_i \) positive), the image is inverted. The sign convention is summarized in Table 1.

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**Figure 3**: Ray diagrams for convex mirror

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Table 1: Sign Convention for Convex Mirrors

<table>
<thead>
<tr>
<th>Object</th>
<th>Image</th>
<th>Sign of ( d_i )</th>
<th>Sign of ( M )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(+)</td>
<td>(-)</td>
<td>Positive</td>
<td>Upright</td>
</tr>
<tr>
<td>(-)</td>
<td>(+)</td>
<td>Negative</td>
<td>Inverted</td>
</tr>
<tr>
<td>Quantity</td>
<td>Conditions</td>
<td>Sign</td>
<td></td>
</tr>
<tr>
<td>--------------------------</td>
<td>-----------------------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>Focal length ( (f) )</td>
<td>Concave mirror</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Convex Mirror</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Convex lens</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Concave lens</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Object distance, ( d_o )</td>
<td>Usually</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Image distance, ( d_i )</td>
<td>Image real</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Image virtual</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Magnification, ( M )</td>
<td>Image upright</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Image inverted</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

**Table 1:** Sign convention for spherical mirrors and lenses

**(B) Spherical Lenses**

The shape of biconvex and biconcave spherical lenses are shown in Figures 4 and 5. A radius of curvature is defined for each spherical surface, but only the focal points (one for each spherical surface) are needed for ray diagrams.

A convex lens is called a **converging lens** because rays parallel to the principal axis converge at the focal point. A concave lens is called a **diverging lens** because rays parallel to the principal axis appear to diverge from the focal point.

As with spherical mirrors, the characteristics of the images formed by spherical lenses can be determined graphically or analytically. In the case of lenses, the chief ray through
the center of a lens is undeviated. A ray parallel to the principal axis is refracted in such a way that it goes through the focal point on transmission through the lens. Also, a focal ray is parallel to the principal axis upon transmission. In the case of a concave lens, the ray appears to have passed through the focal point on the object side of the lens.

If the image is formed on the side of the lens opposite to the object, it is real and can be observed on a screen. However, if the image is on the same side of the lens as the object, it is virtual and cannot be seen on a screen.

The spherical thin-lens equation and magnification factor for analytically determining the image characteristics are identical to the equations for spherical mirrors. The sign convention is also similar. It should be noted that this lens equation applies only to thin lenses.

However, the relationship between the focal length and the radius of curvature for a spherical lens is not as simple as for that of a spherical mirror. For a lens, the focal length is given by what is known as the lensmaker’s equation:

$$\frac{1}{f} = (n - 1)\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

where $n$ is the index of refraction for the lens material and the R’s are taken as positive (negative) for convex (concave) surfaces. The index of refraction of glass with $n = 1.5$ and symmetrical converging lenses ($R_1 = R$ and $R_2 = R$) yields $f = R$. In computations, the experimentally determined value of $f$ will be used.

**Examples:**

1) An object is placed 45 cm in front of a concave mirror with a focal length of 15 cm. See Figure 2. Determine the image characteristics analytically.

**Solution:** With $d_o = 45$ cm and $f = 15$ cm we have from the spherical mirror equation:

$$\frac{1}{45} + \frac{1}{d_i} = \frac{1}{15}$$

We solve this to get:

$d_i = 22.5$ cm

Then, the magnification is given by:

$$M = \frac{-d_i}{d_o} = -\frac{22.5}{45} = -\frac{1}{2}$$
Thus, the image is real (positive di), inverted (negative M), and reduced by a factor of ½ (i.e. one-half as tall as the object).

2) An object is placed 30 cm from a biconcave lens with a focal length of 10 cm. See Figure 4. Determine the image characteristics analytically.

Solution: With \(d_o = 30\) cm and \(f = -10\)cm (negative by convention for a concave lens), we can use the spherical mirror equation as follows:

\[
\frac{1}{30} + \frac{1}{d_i} = \frac{1}{-10}
\]

We solve this to get:

\[d_i = -7.5\] cm

Then,

\[M = \frac{d_i}{d_o} = \frac{(-7.5)cm}{30cm} = +\frac{1}{4}\]

Thus the image is virtual (negative \(d_i\)), upright (positive M), and reduced by a factor of \(\frac{1}{4}\).

3) A convex lens is made of glass with \(n = 1.65\) and has radii of curvature \(R_1=R_2= 42\) cm. Its focal length is calculated as follows:

Use the lens makers formula (Remember that \(R\) is positive for convex surfaces):

\[
\frac{1}{f} = (n-1)(\frac{1}{R_1} + \frac{1}{R_2})
\]

\[
\frac{1}{f} = (1.65 -1)(\frac{1}{42} + \frac{1}{42})
\]

This gives \(f = +32\) cm.

4) A concave lens is made of glass with \(n = 1.65\) and has radii of curvature \(R_1=R_2= 42\) cm. Its focal length is calculated as follows:

Use the lens maker’s formula (Remember that \(R\) is negative for concave surfaces):

\[
\frac{1}{f} = (n-1)(\frac{1}{R_1} + \frac{1}{R_2})
\]
\[
\frac{1}{f} = (1.65 - 1)(-\frac{1}{42} - \frac{1}{42})
\]

This gives \( f = -32 \text{ cm.} \)

5) Assume that the cornea and the crystalline lens of the human eye act together as a single lens placed at a distance of 2.2 cm from the retina. This lens is deformable i.e. it can change its focal length by changing its shape. What must be the focal length if the eye is viewing an object at a distance of 25 cm?

\[
\frac{1}{25\text{cm}} + \frac{1}{2.2\text{cm}} = \frac{1}{f}
\]

\( f = 2.02 \text{ cm} \)
Lab 10: Spherical Mirrors and Lenses

Names:

Part I: Draw ray diagrams to locate the image of the following objects shown in the figures below. Describe each image (i.e. erect or inverted, magnified or diminished, real or virtual). In the figures, F is the focal point and C is the center of curvature.

For example:

i) \( d_o > R \)

![Ray diagram](image)

The image is: Real, Inverted and Reduced

ii) \( f < d_o < R \)

![Ray diagram](image)

The image is:
iii) \( d_o < f \)

The image is:

iv) \( d_o = f \)

The image is:
v) $d_o = R$

The image is:

vi) $d_o > R$

The image is:
$vii) f < d_o < R$

The image is:

$viii) d_o < f$

The image is:
ix) $d_o = f$

The image is:

x) $f < d_o < 2f$

The image is:
$xi) \ d_o < f$

The image is:

$xii) \ d_o > 2f$

The image is:
$\text{xiii)} d_o > 2f$

The image is:

$\text{xiv)} f < d_o < 2f$

The image is:
Conclusions for Part I:

1) What can you conclude for convex mirrors?

2) What can you conclude for convex lenses?

3) What can you conclude for concave lenses?
**Part II:** Use the apparatus provided to find the image distance and magnification for the cases as shown in the Table below:

<table>
<thead>
<tr>
<th>See diagram in Part I for experimental setup</th>
<th>Experimental</th>
<th>Computed</th>
<th>(d_i) percent difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(d_o) (object distance)</td>
<td>(d_i) (image distance)</td>
<td>M factor (estimated)</td>
</tr>
<tr>
<td>i) (d_o &gt; R)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ii) (f &lt; d_o &lt; R)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>iii) (d_o &lt; f)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>vi) (d_o &gt; R)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>viii) (d_o &lt; f)</td>
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<tr>
<td>xi) (d_o &lt; f)</td>
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<tr>
<td>xii) (d_o &gt; 2f)</td>
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<tr>
<td>xiii) (d_o &gt; 2f)</td>
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<tr>
<td>xv) (d_o &lt; f)</td>
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</tbody>
</table>

**Calculations:**