Thin Lens Equation

- Combining the effect of the two surfaces and neglecting \( t \) yields the lens-makers’ equation.
- It can be used to determine the values of \( R_1 \) and \( R_2 \) needed for a given index of refraction and a desired focal length \( f \).
- The relationship among the focal length, the object distance and the image distance is the same as for a mirror.

\[
\frac{1}{p} + \frac{1}{q} = \frac{1}{f}
\]

Focal Length of a Converging Lens

- The parallel rays pass through the lens and converge at the focal point.
- The parallel rays can come from the left or right of the lens.
- There is only one focal length

Focal Length of a Diverging Lens

- The parallel rays diverge after passing through the diverging lens.
- The focal point is the point where the rays appear to have originated.
- There is only one focal length

Determining Signs for Thin Lenses

- The front side of the thin lens is the side of the incident light.
- The light is refracted into the back side of the lens.
- This is also valid for a refracting surface.
Sign Conventions for Thin Lenses

**TABLE 36.3  Sign Conventions for Thin Lenses**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Positive When...</th>
<th>Negative When...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Object location ($p$)</td>
<td>object is in front of lens (real object).</td>
<td>object is in back of lens (virtual object).</td>
</tr>
<tr>
<td>Image location ($q$)</td>
<td>image is in back of lens (real image).</td>
<td>image is in front of lens (virtual image).</td>
</tr>
<tr>
<td>Image height ($h'$)</td>
<td>image is upright.</td>
<td>image is inverted.</td>
</tr>
<tr>
<td>$R_1$ and $R_2$</td>
<td>center of curvature is in back of lens.</td>
<td>center of curvature is in front of lens.</td>
</tr>
<tr>
<td>Focal length ($f$)</td>
<td>a converging lens.</td>
<td>a diverging lens.</td>
</tr>
</tbody>
</table>

Magnification of Images Through a Thin Lens

- The lateral magnification of the image is $M = \frac{h'}{h} = -\frac{q}{p}$.

- When $M$ is positive, the image is upright and on the same side of the lens as the object.

- When $M$ is negative, the image is inverted and on the side of the lens opposite the object.

Thin Lens Shapes

- Converging lenses have positive focal lengths. They are thickest in the middle.

- Diverging lenses have negative focal lengths. They are thickest at the edges.

Ray Diagrams for Thin Lenses – Converging

- Ray diagrams are convenient for locating the images formed by thin lenses or systems of lenses.

- For a converging lens, the following three rays are drawn:
  - Ray 1 is drawn parallel to the principal axis and then passes through the focal point on the back side of the lens.
  - Ray 2 is drawn through the center of the lens and continues in a straight line.
  - Ray 3 is drawn through the focal point on the front of the lens (or as if coming from the focal point if $p < f$) and emerges from the lens parallel to the principal axis.
Ray Diagram for Converging Lens, \( p > f \)

- The image is real.
- The image is inverted.
- The image is on the back side of the lens.

When the object is in front of and outside the focal point of a converging lens, the image is real, inverted, and on the back side of the lens.

Ray Diagram for Converging Lens, \( p < f \)

- The image is virtual.
- The image is upright.
- The image is larger than the object.
- The image is on the front side of the lens.

When the object is between the focal point and a converging lens, the image is virtual, upright, larger than the object, and on the front side of the lens.

Ray Diagrams for Thin Lenses – Diverging

- For a diverging lens, the following three rays are drawn:
  - Ray 1 is drawn parallel to the principal axis and emerges directed away from the focal point on the front side of the lens.
  - Ray 2 is drawn through the center of the lens and continues in a straight line.
  - Ray 3 is drawn in the direction toward the focal point on the back side of the lens and emerges from the lens parallel to the principal axis.

Ray Diagram for Diverging Lens

- The image is virtual.
- The image is upright.
- The image is smaller.
- The image is on the front side of the lens.

When an object is anywhere in front of a diverging lens, the image is virtual, upright, smaller than the object, and on the front side of the lens.
Combinations of Thin Lenses

- The image formed by the first lens is located as though the second lens were not present.
- Then a ray diagram is drawn for the second lens.
- The image of the first lens is treated as the object of the second lens. The image formed by the second lens is the final image of the system.
- If the image formed by the first lens lies on the back side of the second lens, then the image is treated as a virtual object for the second lens.
  - \( p \) will be negative
- The overall magnification is the product of the magnification of the separate lenses.

The image formed by the first lens is located as though the second lens were not present.

Combination of Thin Lenses, example

- Produces a real image.
- Light sensitive component behind the lens where the image is formed (a CCD or film).
- The time interval that the shutter is opened is called the exposure time.

Two Lenses in Contact

- Consider a case of two lenses in contact with each other: The lenses have focal lengths of \( f_1 \) and \( f_2 \).

\[
\frac{1}{p} + \frac{1}{q} = \frac{1}{f_1} + \frac{1}{f_2}
\]

- For the first lens, \( \frac{1}{p} + \frac{1}{q} = \frac{1}{f_1} \).
- For the 2nd, \( \frac{1}{p} + \frac{1}{q} = \frac{1}{f_2} \).
- Since the lenses are in contact, \( p_2 = -q_1 \).
- Hence \( \frac{1}{p} + \frac{1}{q} = 1/f \) where \( f = \frac{1}{f_1} + \frac{1}{f_2} \).
- \( \frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} \).
- The bending power \( (1/f) \) adds.

The Camera

- The photographic camera is a simple optical instrument containing a converging lens or lens combination.
- Produces a real image.
- Light sensitive component behind the lens where the image is formed (a CCD or film).
- The camera is focused by varying the distance between the lens and the CCD.
- The time interval that the shutter is opened is called the exposure time.
Camera, f-numbers

- The f-number of a camera lens is the ratio of the focal length of the lens to its diameter. \( f \)-number = \( f / D \)
- The f-number is often given as a description of the lens “speed”. A lens with a low f-number is a “fast” lens.
- The intensity of light incident on the film is related to the f-number: \( I \sim 1/(f\text{-number})^2 \).

Camera, f-numbers, cont.

- Increasing the setting from one f-number to the next higher value decreases the area of the aperture by a factor of 2.
- The lowest f-number setting on a camera corresponds to the aperture wide open and the use of the maximum possible lens area.
- Simple cameras usually have a fixed focal length and a fixed aperture size, with an f-number of about 11. Most cameras with variable f-numbers adjust them automatically.
- A high value for the f-number allows for a large depth of field. This means that objects at a wide range of distances from the lens form reasonably sharp images on the film.

The Eye

- The normal eye focuses light and produces a sharp image.
- Cornea – light passes through this transparent structure
- Aqueous Humor – clear liquid behind the cornea
- The pupil, A variable aperture opening in the iris
- The crystalline lens (variable)

The Eye – Parts, cont.

- Most of the refraction takes place at the outer surface of the eye where the cornea is covered with a film of tears.
- The iris is the colored portion of the eye. It is a muscular diaphragm that controls pupil size and regulates the amount of light entering the eye.
  - It dilates the pupil in low light conditions.
  - It contracts the pupil in high-light
- The f-number of the eye is from about 2.8 to 16.
The cornea-lens system focuses light onto the back surface of the eye, called the retina which contains sensitive receptors called rods and cones.

- These structures send impulses via the optic nerve to the brain.
  - This is where the image is perceived.
- Accommodation
  - The eye focuses on an object by varying the shape of the pliable crystalline lens through this process.
  - Limited in that objects very close to the eye produce blurred images.

Accommodation

The near point is the closest distance for which the lens can accommodate to focus light on the retina.

- Typically at age 10, this is about 18 cm
- The average value is about 25 cm.
- It increases with age up to 500 cm or greater at age 60.
- The far point of the eye represents the largest distance for which the lens of the relaxed eye can focus light on the retina.
  - Normal vision has a far point of infinity.

The Eye – Operation

The Eye – Near and Far Points

The Eye – Seeing Colors

Only three types of color-sensitive cells are present in the retina.

- They are called red, green and blue cones.
- What color is seen depends on which cones are stimulated.

Farsightedness

- Also called hyperopia
- The near point of the farsighted person is much farther away than that of the normal eye.
- The image focuses behind the retina.
- Can usually see far away objects clearly, but not nearby objects.
- A converging lens can be used to correct the condition.
Nearsightedness

- Also called myopia
- The far point of the nearsighted person is not infinity and may be less than one meter.
- The nearsighted person can focus on nearby objects but not those far away.
- A diverging lens can be used to correct the condition.
- About 30 percent of Americans are nearsighted.

Presbyopia and Astigmatism

- Presbyopia (literally, “old-age vision”) is due to a reduction in accommodation ability.
- The cornea and lens do not have sufficient focusing power to bring nearby objects into focus on the retina.
- Condition can be corrected with converging lenses.
- In astigmatism, light from a point source produces a line image on the retina.
- Produced when either the cornea or the lens or both are not perfectly symmetric.
- Can be corrected with lenses with different curvatures in two mutually perpendicular directions.

Diopters

- Optometrists and ophthalmologists usually prescribe lenses measured in diopters. The power $P$ of a lens in diopters equals the inverse of the focal length in meters.
- $P = 1/f$
- Corrective lenses are typically a few diopters.

Magnifier

- A simple magnifier consists of a single converging lens used to increase the apparent size of an object.
- The size of an image formed on the retina depends on the angle subtended by the eye. When an object is placed at the near point $q \approx 25$ cm, the angle subtended is a maximum and the angular magnification is $M = 1 + 25\text{cm} / f$. When the image is infinity, $M = 25\text{cm} / f$ (few X).
- When the object is placed near the focal point of a converging lens, the lens forms a virtual, upright, and enlarged image.
A compound microscope consists of two lenses and gives greater magnification than a single lens.

The objective lens has a short focal length, \( f_o < 1 \text{ cm} \). The eyepiece has a focal length, \( f_e \), of a few cm.

The lateral magnification by the objective is

\[
M_o = \frac{-L}{f_o}
\]

The angular magnification by the eyepiece of the microscope is

\[
m_e = \frac{25 \text{ cm}}{f_e}
\]

The overall magnification of the microscope is the product of the individual magnifications.

The lenses are separated by a distance \( L \) much greater than either focal length.

The object is placed just outside the focal point of the objective. This forms a real, inverted image. This image is located at or close to the focal point of the eyepiece and acts as the object for the eyepiece.

The image seen by the eye, \( I_2 \), is virtual, inverted and very much enlarged.

Telescopes are designed to aid in viewing distant objects.

Two fundamental types of telescopes

- Refracting telescopes use a combination of lenses to form an image.
- Reflecting telescopes use a curved mirror and a lens to form an image.

Telescopes can be analyzed by considering them to be two optical elements in a row.

The image of the first element becomes the object of the second element.
Refraction Telescope

- The two lenses are arranged so that the objective forms a real, inverted image of a distant object.
- The image is formed at the focal point of the eyepiece.
- \( p \) is essentially infinity
- The two lenses are separated by the distance \( f_o + f_e \) which corresponds to the length of the tube.
- The eyepiece forms an enlarged, inverted image of the first image.
- The angular magnification is \( M = -f_o / f_e \).

Reflecting Telescope, Newtonian Focus

- The incoming rays are reflected from the mirror and converge toward point A.
- At A, an image would be formed.
- A small flat mirror, M, reflects the light toward an opening in the side and it passes into an eyepiece.
- This occurs before the image is formed at A.