Thin Lenses

Objective To explore the thin lens equation, and to learn to distinguish between real and virtual images.

Materials

- Light Source
- Optics Track
- Convex 127 mm focal length lens
- Concave -22 mm focal length lens
- Black magnetic stands
- Crossed Arrow Target (Object)
- Viewing Screen
- Ruler

Theory

The Thin Lens Equation

A thin lens forms an image by bending light according to the law of refraction. The object distance, image distance, and focal length of the lens are related by the thin lens equation:

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$$

Magnification

The magnification of an image is defined to be the height of the image divided by the height of the object:

$$m = \frac{y_i}{y_o}$$

The magnification can be determined by simply knowing the image distance and the object distance via the relationship:

$$m = -\frac{d_i}{d_o}$$

A few important notes about signs:

- Image distance:
    - The image distance is positive if the refracted light rays actually cross on the opposite side of the lens as the object (a real image).
    - The image distance is negative if the refracted light rays do not actually cross, but instead appear to diverge from the same side of the lens as the object (virtual image).
- Focal length:
    - The focal length is positive if a set of parallel rays incident on the lens focuses to a point on the opposite side of the lens from the incident rays. A convex lens is such a lens.
    - The focal length is negative if a set of parallel rays incident on the lens defocuses such that they appear to diverge from a point on the same side of the lens as the incident rays. A concave lens is such a lens.
- Magnification:
    - The magnification is positive if the image is oriented in the same way as the object (upright).
    - The magnification is negative if the image is oriented in the opposite way as the object (inverted).

Principal Ray Diagrams for Thin Lenses

A pictorial method to predict the location and height of an image is called a "Principal Ray Diagram". In a principal ray diagram, we determine where rays leaving the object will cross (in the case of a real image) or appear to cross (in the case of a virtual image). This crossing (or apparent crossing) point is the location of the image. To determine this location of crossing (or apparent crossing), we use the following facts about thin lenses.

- The center of the lens is "flat". Therefore, no bending occurs for a light ray directed through the center of the lens.
- The focal points of the lens (there are two, on opposite sides of the lens and equally distant from the lens) are defined so that rays parallel to the optic axis refract either to the focal point (for a converging lens) or away from the focal point (for a diverging lens).

With these rules in mind, the image can be found by drawing the three principal rays as follows:

Converging Lens (positive focal length)

1. Draw a ray from the object tip to the center of the lens. The ray goes straight through without bending.
2. Draw a ray from the object tip parallel to the optic axis. The ray refracts through the far focal point.

3. Draw a ray through both the object tip and near focal point. The ray refracts parallel to the optic axis.

Diverging Lens (negative focal length)

1. Draw a ray from the object tip to the center of the lens. The ray goes straight through without bending.
2. Draw a ray from the object tip parallel to the optic axis. The ray refracts away from the near focal point.
3. Draw a ray from the object tip towards the far focal point. The ray refracts parallel to the optic axis.

Procedure

Part I: Real Images

Principal Ray Diagrams:

We will be using a 127 mm focal length convex (converging) lens and placing an object at various distances from the lens. To get a feel for the images we expect, we will first do several principal ray tracing diagrams.

Trial 1 Ray Tracing

In this trial, the object will be placed 55.0 cm from the 127 mm (12.7 cm) focal length lens. On a separate sheet of white paper, complete a ray tracing diagram for this scenario.

You must use a ruler to properly scale the diagram. In other words, with an object distance of 55.0 cm and a focal length of 12.7 cm, your object should be a factor of 55/12.7 = 4.33 times further from the lens than your focal point.

You will turn this ray tracing in with your lab.

1. *Based on your ray tracing, is the image real or virtual? Explain briefly how you can tell.

2. *Based on your ray tracing, is the image upright or inverted?

3. *Based on your ray tracing, is the image smaller or larger than the object?

Trial 2 Ray Tracing

In this trial, the object will be placed 35.0 cm from the 127 mm (12.7 cm) focal length lens. On a separate sheet of white paper, complete a ray tracing diagram for this scenario. As before, you must use a ruler to properly scale the diagram. **Turn this ray tracing in with your lab.**

1. *Based on your ray tracing, is the image real or virtual? Explain briefly how you can tell.

2. *Based on your ray tracing, is the image upright or inverted?

3. *Based on your ray tracing, is the image smaller or larger than the object?

Trial 3 Ray Tracing

In this trial, the object will be placed 15.0 cm from the 127 mm (12.7 cm) focal length lens. On a separate sheet of white paper, complete a ray tracing diagram for this scenario. As before, you must use a ruler to properly scale the diagram. **Turn this ray tracing in with your lab.**

1. *Based on your ray tracing, is the image real or virtual? Explain briefly how you can tell.

2. *Based on your ray tracing, is the image upright or inverted?

3. *Based on your ray tracing, is the image smaller or larger than the object?

Viewing the Images and Making Measurements

1. Find the light source and the optics track. Place your light source on one end of the optics track so that the light opening is pointing down the track.

2. Plug your light source in and turn it on. Note that light should be shining down the track. Make sure the knob on the light source is oriented such that your light is shining straight ahead down the track.

3. Now find the "Crossed Arrow Target". The arrow on the Crossed Arrow Target will be your "object".

4. *With your ruler or the ruler on the target, measure the length (to the nearest half mm!) of arrow. This is the height y_o of your object. Record your value below, in cm.

   Write your value here: y_o = ___________________

5. Using the magnets on the back of the crossed arrow target, attach it to the light source, so that the light is shining directly through it and down the track.

6. Find the white square labeled "Viewing Screen".

7. Find one of the black metal squares with a square hole in it. We will call this a "stand". Place the stand on your track. It should magnetically stick to the track.

8. Attach the viewing screen to the stand so that the viewing screen is covering the hole in the holder and facing the light source.

9. In your kit, find the 127 mm focal length convex lens and attach it to a stand.

10. Place the stand on the track so that the lens itself is <u>exactly</u> 55.0 cm from the object (the crossed arrow target) and in between the object and the viewing screen. You can use the measuring tape on the side of the track to make sure the distance is correct. Thus, the object distance d_o (the distance from object to lens) will be 55.0 cm.

11. Move the viewing screen back and forth along the track until you get a sharp, clear image on the screen *(note: it may be small, but it should be sharp and clear!*)

12. Using the measuring tape along the track (and additional meter stick if needed), measure the distance from the lens to the image and **record it, in cm, in the data table in the "Measured Image Distance" column.**

13. **Record whether the image is upright or inverted in the Data Table.** *Hint: You may find it helpful to use one of the other convex lenses from your optics kit as a magnifying glass to see the image more clearly.*

14. Use your ruler to measure the height of the image and **record it in the table under "Measured Image Height", in cm**. *Hint: You may find it helpful to use one of the other convex lenses from your optics kit as a magnifying glass to see the image more clearly.*

15. Repeat steps 10-14 for object distances of 35.0 cm and 15.0 cm.

Object Distance d_o	Predicted Image Distance $d_{i,theo}$	Measured Image Distance $d_{i,exp}$	Predicted Image Height $y_{i,theo}$	Measured Image Height $y_{i,exp}$	Upright or Inverted?
55.0 cm					
35.0 cm					
15.0 cm					

Data Table for 127 mm focal length convex lens

16. *Discuss how well the images in your principal ray diagrams matched your experimental images. The discussion should include the orientations of the images and the sizes of the images.

Calculations and Analysis

Now we will use the thin lens and magnification equations to determine the theoretical image distances and theoretical image heights for our trials.

1. *Use equation (1) (the thin lens equation) to calculate the predicted image distance for an object distance of 55.0 cm and focal length of 12.7 cm. **Enter your value in the data table in the "Predicted Image Distance" column**. **Show your work below!**

2. Repeat for the other two object distances. **Enter the values in the data table in the "Predicted Image Distance" column**. You do not need to show your work here.

3. *Are your calculated image distances positive or negative? What does this tell you about the type of image your mirror made? Does this match the type of images that you observed in your experiment? Explain.

4. *Use your result for the predicted image distance, the height of your object y_o, as well as equations (3) and (2) to calculate the predicted height of your image for the 55.0 cm object distance. **Enter your value into the "Predicted Image Height" column**. **Show your work below!**

5. Repeat step 4 for the other two object distances. **Enter the values in the data table in the "Predicted Image Height" column**. You do not need to show your work here.

6. *Note the signs of the "Predicted Image Heights". Do these match your observations in the "Upright or Inverted?" column in the data table? **Explain briefly.**

7. *How do the predicted image distances and heights compare to the experimentally measured values? **Discuss any sources of error which may have caused them to differ.**

Part II: Virtual Images

Converging Lens

1. *Now move your object distance to 10.0 cm (still with the 127 mm convex lens). Note that this distance is less than the focal length of the lens. As in Part I, try to find a sharp image on your viewing screen. **Record below whether you can find such an image. If not, explain why below.**

2. *Instead of trying to find an image on the viewing screen, look directly through the lens with your eye towards the light source. In the space below, record whether the image you see is upright or inverted. Also record whether the image appears to be significantly larger or smaller than the object.

   Inverted or upright?: ______________________________

   Size compared to object?:___________________________

3. On a separate sheet of paper, complete a ray tracing diagram for this situation. As before, you must use a ruler to properly scale the diagram. **Turn this ray tracing in with your lab.**

4. *Based on your ray tracing, is the image real or virtual? Explain briefly how you can tell.

5. *Based on your ray tracing, is the image upright or inverted?

6. *Based on your ray tracing, is the image smaller or larger than the object?

7. *Discuss whether the ray tracing diagram qualitatively matches what you saw when you looked through the lens.

8. *Now, use the thin lens equation and the magnification equation to calculate the

   (i) image distance
   (ii) the magnification of the image.

   Show your work below and then record the values in the provided spaces below.

d_i = ________________________ m = _____________________

9. *What is the sign of d_i in your calculation? What does this tell you about the type of image you expect? Does this match what you observed?

10. *What is the sign of m in your calculation? What does this tell you about the orientation of the image you expect? Does this match what you observed?

11. *Does the value of m match what you saw in your observation of the image? Explain briefly.

Diverging Lens

1. *Now switch out your lens for a -22 mm concave lens. This is a double concave lens and as such causes parallel incident light rays to diverge. Thus, it is called a **diverging lens**. Place your object 10.0 cm from the lens. Try to find a sharp image on your viewing screen. Record below whether you can find such an image. If not, explain why below.

2. *Instead of trying to find an image on the viewing screen, now look directly through the lens with your eye. In the space below, record whether the image is upright or inverted.

Also record whether the image appears to be significantly larger or smaller than the object.

Inverted or upright?: ____________________________

Size compared to object?:_________________________

3. On a separate sheet of paper, complete a ray tracing diagram for this situation. As before, you must use a ruler to properly scale the diagram. **Turn this ray tracing in with your lab.**

4. *Based on your ray tracing, is the image real or virtual? Explain briefly how you can tell.

5. *Discuss whether the ray tracing diagram qualitatively matches what you saw when you looked through the lens.

6. *Now, use the thin lens equation and the magnification equation to calculate the

   (iii) image distance
   (iv) the magnification of the image.

   Show your work below and then record the values in the provided spaces below.

$d_i =$ ______________________ $m =$ ____________________

7. *What is the sign of d_i in your calculation? What does this tell you about the type of image you expect? Does this match what you observed?

8. *What is the sign of m in your calculation? What does this tell you about the orientation of the image you expect? Does this match what you observed?

9. *Does the value of m match what you saw in your observation of the image? Explain briefly.

10. *Now move the lens around to try several different object distances for the diverging lens.
    a. Can you find a sharp, real image for any of them? What does this tell you about the type of image created by the diverging lens?
    b. For each object distance that you try, look through the lens.
        i. Is the image upright or inverted?

ii. Is the object larger or smaller than the object?

Summary Questions:

1. Using your observations from the experiments, as well as the ray diagrams and calculations that you've done, answer the following questions about **converging** lenses:

For $d_o > 2f$

i. Is the image real or virtual?

ii. Is the image upright or inverted?

iii. Is the image closer to the lens or further from the lens than the object?

iv. Is the image larger than the object or smaller than the object?

For $2f > d_o > f$

i. Is the image real or virtual?

ii. Is the image upright or inverted?

iii. Is the image closer to the lens or further from the lens than the object?

iv. Is the image larger than the object or smaller than the object?

For $d_o < f$

i. Is the image real or virtual?

ii. Is the image upright or inverted?

iii. Is the image closer to the lens or further from the lens than the object?

iv. Is the image larger than the object or smaller than the object?

2. Using your observations from the experiments, as well as the ray tracings and calculations that you've done, answer the following questions about **diverging** lenses:

   For all s:

   i. Is the image real or virtual?

   ii. Is the image upright or inverted?

   iii. Is the image closer to the lens or further from the lens than the object?

   iv. Is the image larger than the object or smaller than the object?

3. Which type of lens, converging or diverging, allows for a greater variety of image types, distances, and magnifications? Discuss.