Thin Lenses

Physics 102 **Workshop #10** **Mar. 24 – Mar. 28, 2008**

Name: ______________________________ **Instructor: ____________**
Lab Partner(s): _______________________ **Time of Workshop: _____**

General Instructions

- Workshop exercises are to be carried out in **groups of three.**
- **One report per group** is due by the end of the class.
- Each week's workshop session would typically contain **three sections**.
    1. A pre-lab reading and assignment section
    2. Experiment section
    3. Practice questions and problems

This lab session is devoted to understanding how images are formed using lenses.

Please make all distance measurements in centimeters and angle measurements in degrees.

COMPREHENSIVE EQUIPMENT LIST

1. Convex lens
2. Optics bench with attached scale reading in millimeters
3. Illuminated object, to be mounted on optics bench
4. Viewing screen, scale in millimeters, mounted on optics bench with scale vertical
5. Convex lens on lens holder
6. Concave lens on lens holder

PART I: Pre-lab reading assignment

Objects
In the context of this lab, an *object* is something that a lens makes an image of.

Some objects are physical objects, things made of atoms. Other objects are images created by any number of various optical components, mirrors or lenses. A lens can make an image of this sort of object just as easily as it can make an image of a physical object.

Physical objects are always "in front" of the lens, but the other kind of object can be either "in front" of the lens or "behind" it. If an object is "in front" of its lens, it is called a ***real object***. If an object is "behind" its lens, it is called a ***virtual object***. Thus, physical objects are always real, but other kinds of objects can be either real or virtual.

What it means to have an object "in front" of its lens is probably familiar to you. Think of looking at a bug with a magnifying glass. However, the idea of an object "behind" its lens most likely is confusing. You need a good example, so that you can see what it means. You will get that example at the end of this lab. In the meantime, you will have to be patient as the sections of this pre-lab reading assignment insist in drawing diagrams sometimes with the object of the lens "in front" of the lens and sometimes with the object of the lens "behind" the lens.

Rays

When something emits light, like the sun or a candle, we think of it as sending *rays* – thin lines of light – in all directions. Then, when some of the rays from the light source strike a physical object, the physical object sends rays out in all directions. If the physical object is in front of a lens, some – but not all – of the rays from the physical object strike the lens and are bent by the lens. Figure 1 shows rays sent out from the tip of an arrow, some of which strike a lens. There is a light source that is not shown. Also, all other points on the arrow send out rays, just as the tip of the arrow does, but the rays from those other points are not shown.

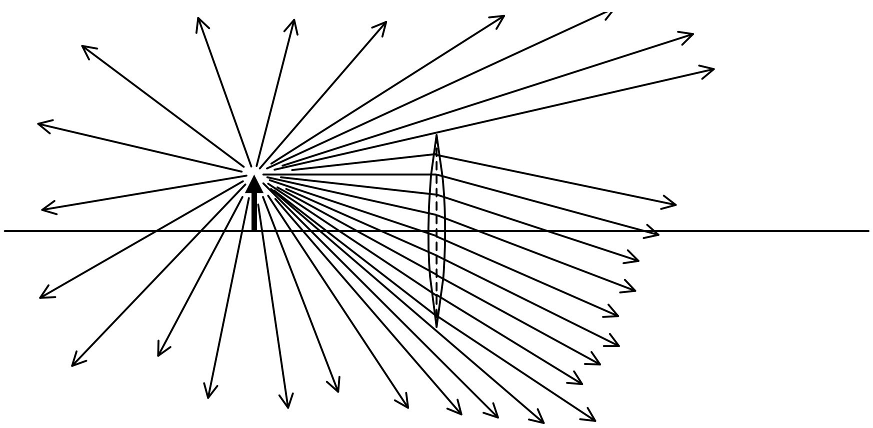


Figure 1

CONVEX AND CONCAVE LENSES AND THEIR FOCAL POINTS

Convex lenses bulge outward in the middle. Concave lenses are thinner at the middle than at the edges. See fig. 2 for side views of concave and convex lenses.

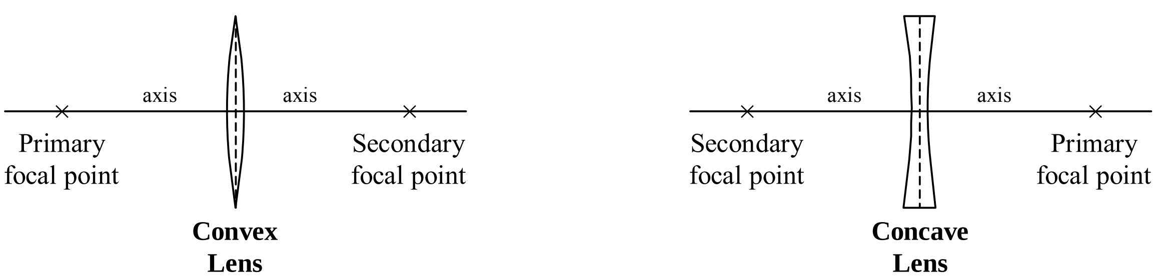


Figure 2: Convex and concave lenses

Each lens has two focal points, a primary focal point and a secondary focal point. Both focal points are at the same distance from the lens but on different sides of the lens. Note that the primary and secondary focal points for a concave lens are on opposite sides of the lens compared to convex lenses.

The distance from the middle of the lens to the focal points is called the **focal length** of the lens. For convex lenses, the focal length is positive, and, for concave lenses, the focal length is negative.

Example: If a lens has a focal length of **-340 millimeters**, you know that the lens is concave, and the distance from the middle of the lens to the focal points is 340 milliimeters.

The line through the middle of a lens is called the axis of the lens.

Figure 2 is drawn assuming that light rays approach the lenses from the left. Convex lenses always have their primary focal points on the side of the lens from which the light rays approach, and concave lenses always have their primary focal points on the opposite side of the lens.

Rules for bending special rays through lenses

To take at random any one of the infinite number of rays that strike a lens and determine exactly how it bends upon passing through a lens is very difficult. However, there are three rays – of the infinite number that strike a lens – for which it is relatively easy to determine how they bend.

The table below gives the rules for drawing each of these three rays and for determining how they bend. After examining this table, look at the examples.

Ray	Incident ray is defined by:	Exit ray is defined by:
1	Tip of object and primary focal point	Point where incident ray intersects lens and running parallel to the lens axis
2	Tip of object and running parallel to the lens axis	Point where incident ray intersects lens and the secondary focal point
3	Tip of object and Center of lens	Exit ray is the same as the incident ray

Here is a summary of how the focal points and the center of the lens are used to determine Rays 1, 2, and 3.

Ray 1 The primary focal point defines the incident ray (the other defining point is the tip of the object).

Ray 2 The secondary focal point defines the exit ray (the other defining point is where the incident ray meets the middle of the lens).

Ray 3 The center of the lens defines the ray (the other point is the tip of the object).

Example of Ray 2 using a concave lens and a real object

This first example is done in steps, so you can see exactly how the lines are drawn. Figure 3 shows a concave lens, with its two focal points, and the real object, represented by an upright arrow.

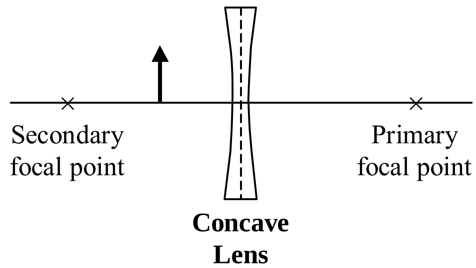


Figure 3: Concave lens and real object (arrow)

Add to Figure 3, the line that defines the incident ray for Ray 2 in Table 1. According to the directions for Ray 2 in Table 1, this must be the line that passes through the tip of the arrow and is parallel to the axis of the lens. The result is shown in Figure 4.

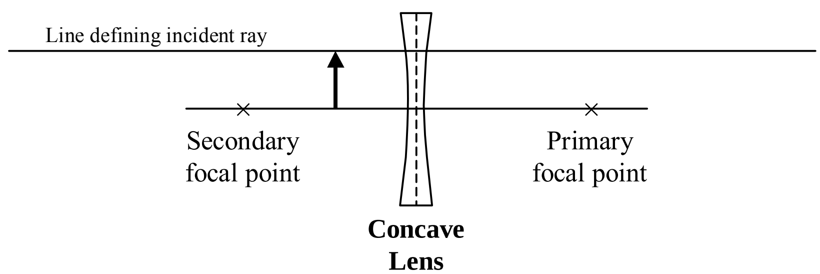


Figure 4: The first step in constructing Ray 2 for the configuration of fig. 3. The line defining the incident ray passes through the tip of the arrow and is parallel to the axis.

Next, add to fig. 4 the line defining the exit ray. According to the directions for Ray 2 in Table 1, this line is defined by two points: the point at which the incident ray intersects the lens and the secondary focal point. The result is shown in fig. 5.

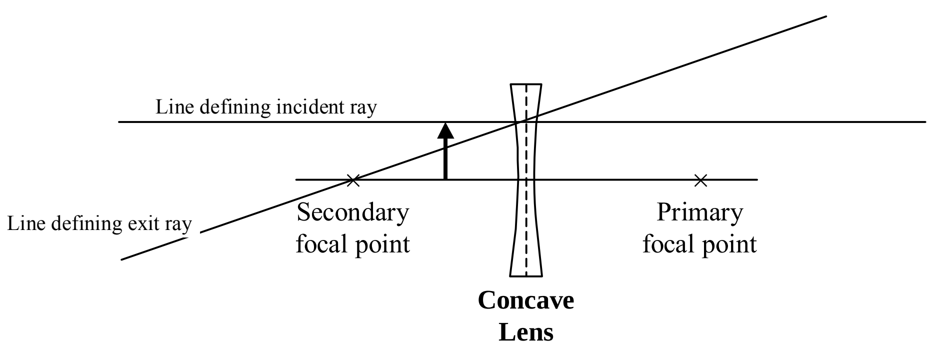


Figure 5: The second step in constructing Ray 2 for the configuration of Figure 3. The line defining the exit ray is now added.

Finally, one can trace how the incident ray is bent on passing through the lens by starting on the left with the line defining the incident ray, moving to the right, and switching to the line defining the exit ray upon passing the lens. See fig. 6.

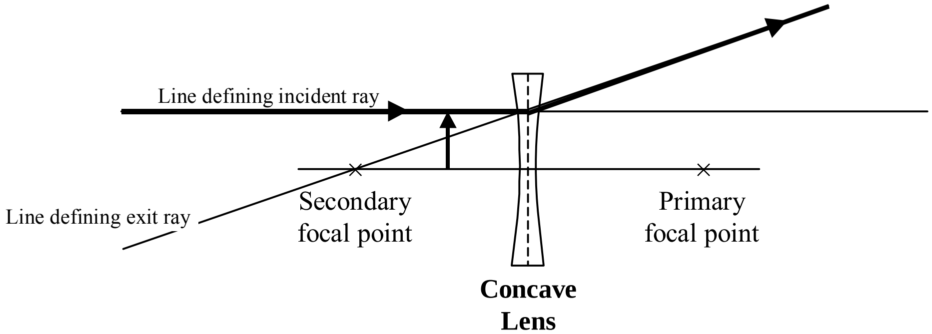


Figure 6: The third step in constructing Ray 2 for the configuration of Figure 3. The bold line shows how the incident ray bends on passing through the lens.

Note the ray is drawn so that it bends at the middle of the lens rather than at one of the curved surfaces.

Example of Ray 1 using a convex lens and a virtual object

In fig. 7 you see a Ray 1 from Table 1. Note that the object (represented by the arrow) is virtual, so it is located "behind" the lens. This in no way complicates the application of the rules in Table 1.

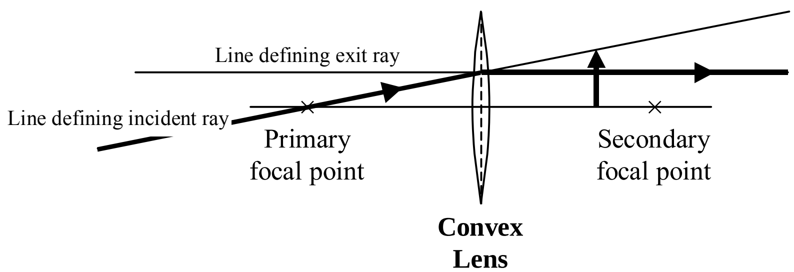


Figure 7: Construction of Ray 1 for a convex lens with a virtual object.

The line defining the incident ray is a straight line between two given points, the primary focal point and the tip of the object. The line defining the exit ray is the straight line that intersects the incident ray in the lens and that is parallel to the axis of the lens.

Example of Ray 3 using a concave lens and a virtual object

For Ray 3, the tip of the object (represented, as usual, by an arrow) and the center of the lens defines both the incident and the exit ray. See Figure 8.

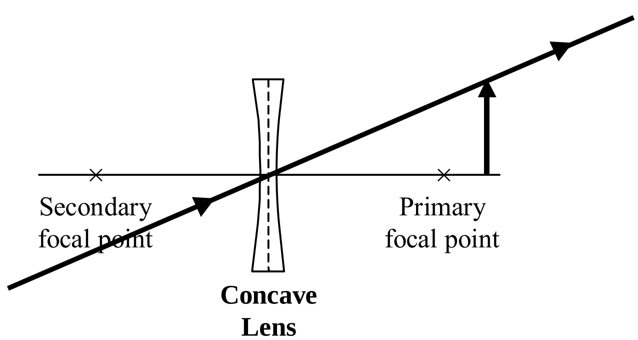


Figure 8: Construction of Ray 3 for a concave lens with a virtual object. The ray is defined by the tip of the object and the center of the lens, and it does not bend.

Locating the image of an object

Given a lens and an object, do the following to locate the image of the object.

- First, construct the three lines defining the incident rays for Rays 1, 2, and 3.
- Second, construct the corresponding three lines defining the exit rays.
- Third, the three lines defining the exit rays will intersect at a point. That point is the location of the tip of the image.

The exit rays themselves may not intersect. It is the lines that define the exit rays that do intersect. If you look only at the exit rays, you may have to extend them forward or backward to find the intersection point.

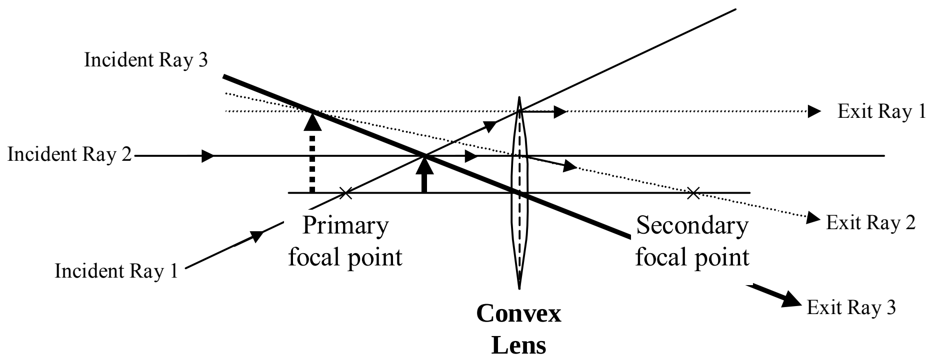


Figure 9: The lines that define the three exit rays intersect at a single point. That point is the location of the tip of the image.

Figure 9 shows an example of using Rays 1, 2, and 3 to locate an image. For Rays 1 and 2, the lines defining the incident rays are solid (as is the object), and the lines defining the corresponding exit rays are dashed (as is the image). The line defining Ray 3, which does not bend, is solid and thicker than the other lines, to make it stand out.

LENS FORMULAE

The following two sections, on *image location* and *image magnification*, describe two lens formulae needed for this lab.

Image location

In the following, it is assumed that light rays travel from left to right, as is all diagrams in this lab handout.

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

f - is the focal length of the lens. It may be positive or negative, depending on whether the lens is convex or concave.

$\mathbf{d_o}$ - is the distance of the object from the lens. It is positive if the object is real (on the left side of the lens), and it is negative if the object is virtual (on the right side of the lens).

d_i - is the distance of the image from the lens. It may be either positive or negative, and the rule for its sign is exactly the opposite of the rule for d_o. d_i is positive if the image is on the right side of the lens (a *real* image), and d_i is negative if the image is on the left side of the lens (a *virtual* image).

Image magnification

The magnification, m, of a lens is how many times taller the image is than the object. By this definition,

$$m \equiv \frac{h_i}{h_o}$$

m - is the magnification. The magnification is negative if the image is up-side-down compared to the object; otherwise the magnification is positive.

h_o - is the height of the object. In ray diagrams, ho is always oriented upward, and its value is always positive.

h_i - is the height of the image. h_i may be either positive or negative. In ray diagrams, it is positive if the image is oriented upward, and it is negative if the image is oriented downward.
m can also be calculated from the object and image distances.

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

d_i and d_o are as described in the previous section and so can be either positive or negative.

Locating objects on the optical bench

Lenses and the small optical screen used on the optical bench in this lab are mounted on a small metal bracket that slides back and forth on the optical bench. On the foot of the small metal bracket – called a *component carrier* – is a white tic mark that can be used to locate the position of the component carrier with respect to the millimeter graduated scale on the optical bench. The idea is to be able to quickly and easily determine the distances between the components (lenses, screen, illuminated object) mounted on the optical bench.

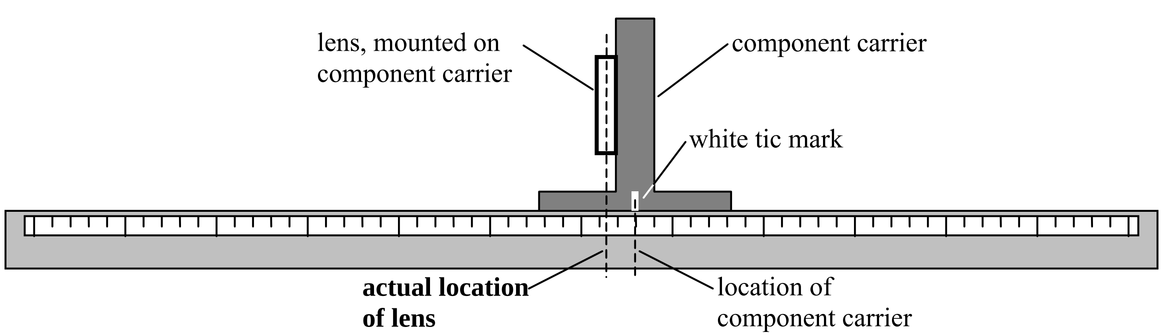


Figure 10: A component carrier holding a lens on the optical bench

The problem is that the location of the optical component mounted on the component carrier is not the same as the location of the white tic mark, as fig. 10 illustrates.

Therefore, be careful to determine the correct location of the component and not the location of the component carrier. The correct location of components depends a little on the component. See Table 2.

Component	*Reference point on component*	*Offset from tic mark*
Lens	center of lens	6 mm
white screen	front face of screen	5 mm
illuminated object	face of illuminated object	0 mm (no tic mark ...)

Table 1: Optical component reference points for determining location on the optical bench.

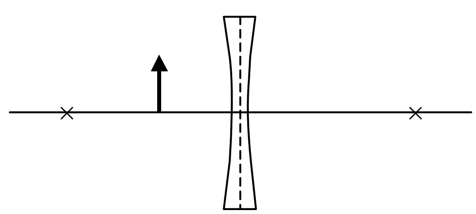
PART II: Pre-lab assignment

1. In the context of thin lenses, what is the difference between real and virtual objects?

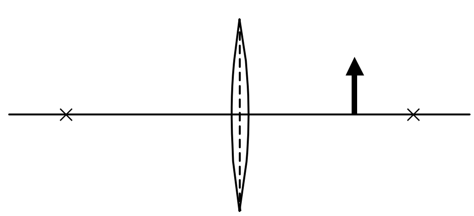
2. Compare the locations of primary and secondary focal points for convex and concave lenses.

3. A lens forms an image of an object. The object distance is 80 mm, and the image distance is -120 mm. Find the focal length of the lens. What type of lens is this ?

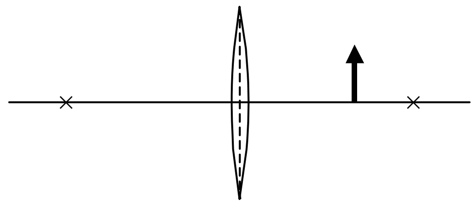
4. Use a straight edge to draw a ray diagram showing how a Ray 1 bends when it passes through the lens in the diagram below. The result should show the bending ray the way the examples above do (the bent ray is dark and with arrows showing its direction).



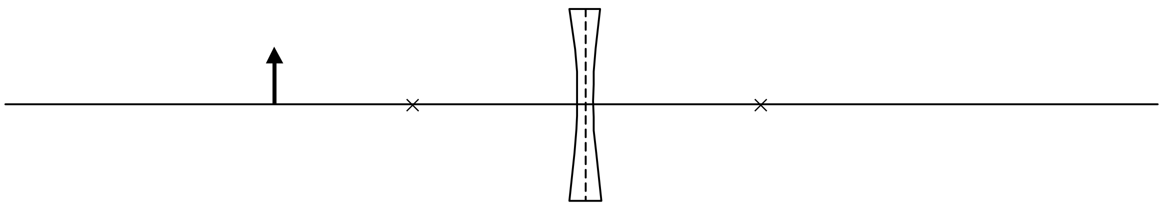
5. Use a straight edge to draw a ray diagram showing how a Ray 2 bends when it passes through the lens in the diagram below. The result should show the bending ray the way the examples above do (the bent ray is dark and with arrows showing its direction).



6. Use a straight edge to draw a ray diagram showing how a Ray 3 bends when it passes through the lens in the diagram below. The result should show the bending ray the way the examples above do (the bent ray is dark and with arrows showing its direction).



7. Use a straight edge to draw a ray diagram using Rays 1, 2, and 3 to locate the image for the diagram below.



PART III: Ray diagrams for convex lens

In order to understand how the images are formed in the next part, you are to construct ray diagrams that approximately represent the situations that you will be working with when you do your next part.

Measuring focal length

Drawing ray diagrams

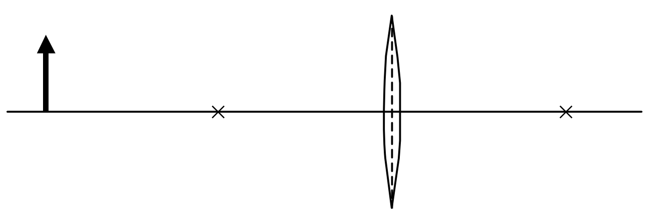


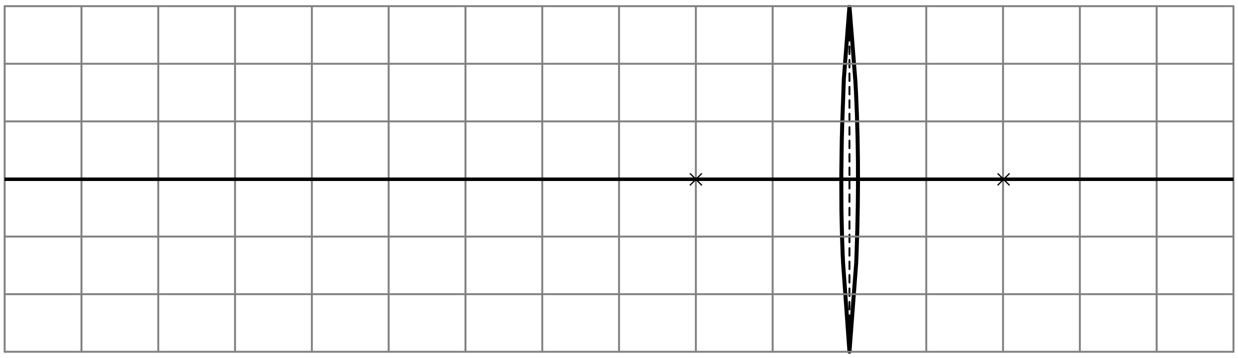
Figure 11

Follow the instructions below and make all necessary diagrams in the space provided below the instructions.

1. Add to the diagram an upward-pointing arrow, representing an object, that is 20 mm high and located a distance 2f to the left of the center of the lens. Figure 11 shows how the diagram will look after you have added the arrow representing the object.

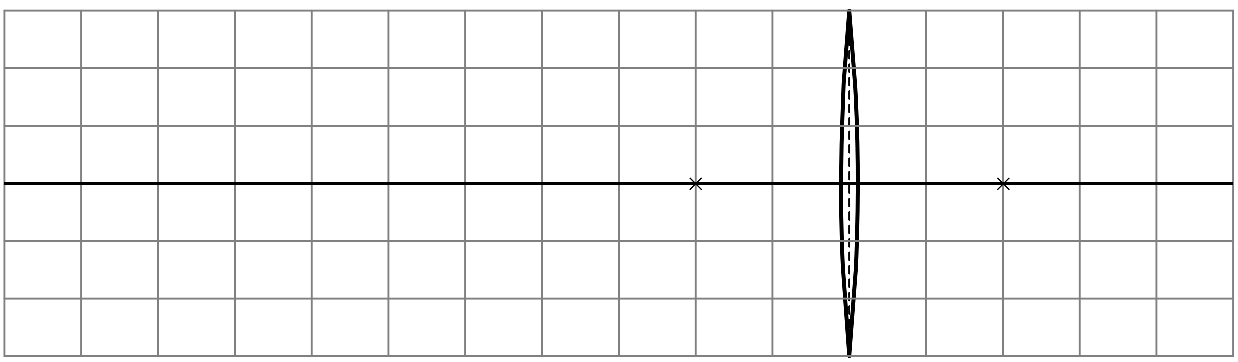
2. Use the ruler and a sharp pencil to draw Rays 1, 2, 3 and locate the image. Refer to part I of this hand out if necessary.

$d_o \approx 2f$



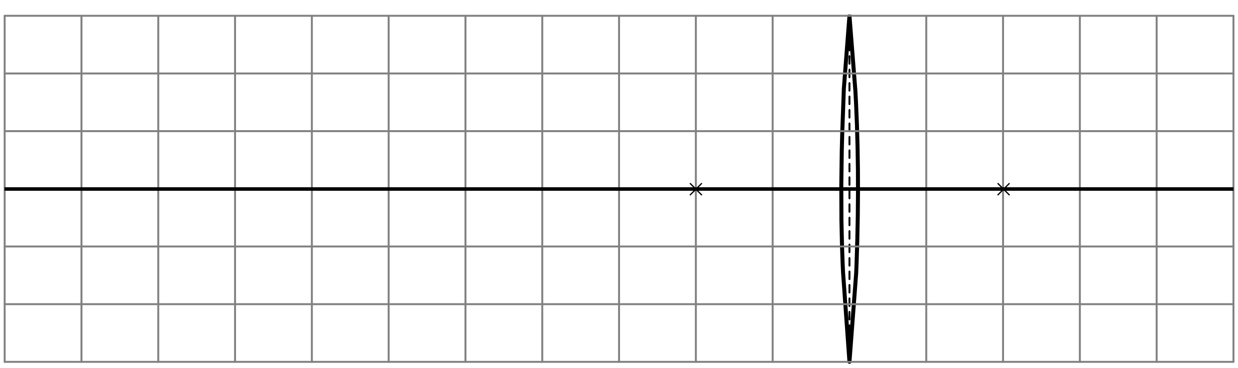
3. Locate the object at about 3.5*f* instead of 2*f* in the space below and repeat steps 1 and 2.

$d_o \approx 3.5f$



4. Locate the object at about 5*f* instead of 2*f* in the space below and repeat steps 1 and 2.

$d_o \approx 5f$



PART IV: Measuring focal length of convex lens

Identify the convex lens using your sense of touch. Follow the instructions below to fill out row one of table 2.

1. Place the illuminated object at one end of the optics bench so that the object is 100 mm from the left end.
2. Place the convex lens approximately 240 mm in front of the illuminated object (distance between object and lens: $d_o \approx 240$ mm).
3. Record the exact value of d_o in Table 3. Since the object is real, d_o is positive.
4. Turn off your desk lamps (if you had them on!). Place the viewing screen on the optics bench on the side of the lens opposite the illuminated object, and move the screen back and forth until you obtain the sharpest image.
5. Record the distance from the lens to the image in Table 3 as d_i. Since the image is real, d_i is positive.
6. Calculate f and m_d (m_d is the magnification calculated using object and image distances) from d_o and d_i, and record the results in Table 3. Refer to part I for the necessary formulae.
7. Measure the object height and the image height (include the correct signs), and record the values as h_o and h_i in Table 3. (Take the height to be the distance between the base of the vertical arrow and its tip. The height is positive if the arrow points upward, and the height is negative if the arrow points downward.)
8. Calculate m_h (m_h is the same magnification but calculated from object and image heights) from h_o and h_i, and record the result in Table 3.
9. Repeat steps 1 – 8 with object distances d_o of approximately 420 mm and 600 mm.

d_o (mm)	d_i (mm)	f (mm)	m_d from d_o & d_i	h_o (mm)	h_i (mm)	m_h from h_o & h_i

Table 2: Focal length of the convex lens

10. The three values of the focal length should be approximately the same. To measure how well they agree, calculate the average value and a percentage discrepancy.

$$f_{average} = \frac{f_{240\ mm} + f_{420\ mm} + f_{600\ mm}}{3}$$

$f_{average}$ = ______ **mm**

$$Discrepancy = \frac{\frac{1}{2}\left(f_{biggest} - f_{smallest}\right)}{f_{average}} \times 100$$

***Discrepancy* = ______ %**

11. The magnifications should all be different, but the same magnification calculated from the d_o, d_i and from the h_o, h_i should be reasonably close. To see how accurate the measured magnification values are, use the following formulae.

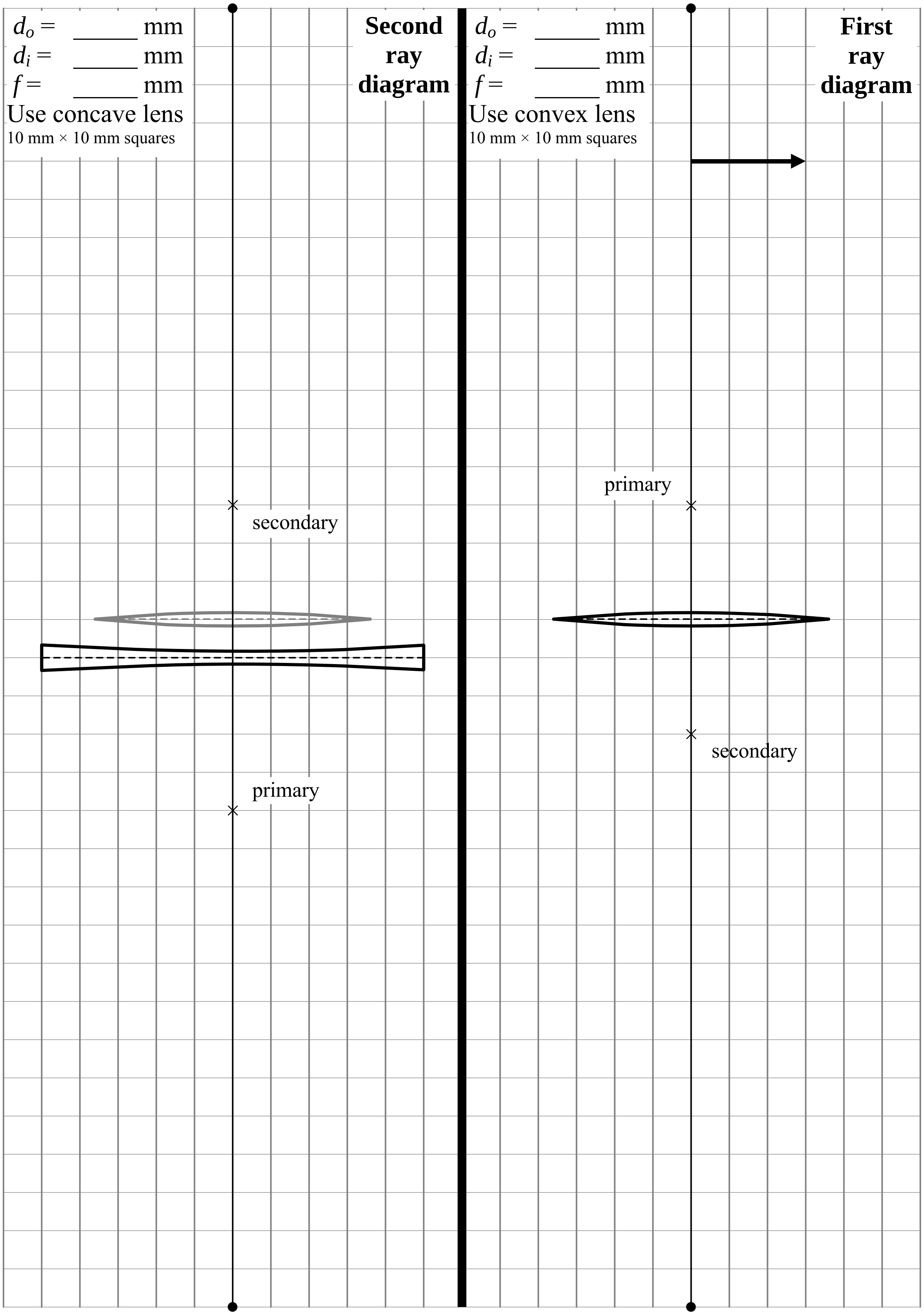
$m_{average} = ½(m_d + m_h)$

$$Discrepancy = \frac{\frac{1}{2}\left|m_d - m_h\right|}{m_{average}} \times 100$$

d_o (mm)	$m_{average}$	*Discrepancy*
		%
		%
		%

PART V: Ray diagrams for measuring concave lens focal length

1. On the first ray diagram in the next page, containing only a convex lens and, on the left, a real object, construct the image of the object.
2. By counting squares in the first ray diagram, determine the values for d_o, d_i, and f, and write them into the places provided in the first ray diagram. (Each square 10 mm x 10 mm).
3. Copy the image you just constructed to the second ray diagram that is next to the first. The copied image must be in the same location and must have the same height and orientation as the image in the first ray diagram. You will use this second ray diagram to determine what happens to the image when a concave lens is inserted between the convex lens and its image.
4. The image you just copied onto the second ray diagram is now a virtual object for the concave lens. Construct the concave lens's image of this virtual object. Refer to part I if necessary. Use Rays 1, 2, and 3.
5. By counting squares in the second ray diagram, determine the values for d_o, d_i, and f, and write them into the places provided in the second ray diagram. Be sure to measure relative to the concave lens and to include the correct signs.


First ray diagram
d_o = ______ mm
d_i = ______ mm
f = ______ mm
Use convex lens
10 mm × 10 mm squares
primary
secondary
Second ray diagram
d_o = ______ mm
d_i = ______ mm
f = ______ mm
Use concave lens
10 mm × 10 mm squares
secondary
primary

PART VI: Measuring concave lens focal length

1. *Overview* – Just read steps a – d; do not do anything.
    a. You will set up the convex lens to form a real image.
    b. You then insert the concave lens between the convex lens and its image, making the image a virtual object for the concave lens.
    c. By locating the virtual object and its image with respect to the concave lens, you can determine the focal length of the concave lens.
    d. By measuring the height and orientation of the virtual object and its image, you can determine the magnification of the concave lens.
2. With the illuminated object at the left end of the optics bench, place the convex lens on the optics bench about 360 mm to the right of the illuminated object.
3. One person in your group uses the screen to locate the image as carefully as possible. **This image will be the virtual object for the concave lens.** Record its location on the optics bench here.

Position of virtual object on optics bench: _______ mm

The only purpose of the convex lens is to create the virtual object. From now on, you ignore the convex lens but work with the properties of the virtual object it created.

4. Measure the height of the virtual object and enter it into the first row of Table 5 in the h_o column.
5. Place the concave lens on the optics bench about 100 mm to the left of the virtual object.
6. Determine the object distance of the virtual object with respect to the concave lens and enter it into the first row of Table 5 in the d_o column. *Since the object is virtual, d_o is a negative number.*
7. Use the screen to locate the image of the virtual object. Do this as carefully as possible.
8. Determine the image distance with respect to the concave lens and enter it into the first row of Table 5 in the d_i column. The image is real, so d_i is a positive number.
9. Finally, determine the image height and enter it into the first row of Table 5 in the h_i column.
10. From the measurements recorded in the first row of Table 3 calculate f, m_d, and m_h.

d_o (mm)	d_i (mm)	f (mm)	m_d from d_o & d_i	h_o (mm)	h_i (mm)	m_h from h_o & h_i

Table 3: Focal length of the concave lens

11. Move the convex lens to about 400 mm in front of the illuminated source and repeat steps 4 – 10 and fill out row 2 in Table 5.
12. Move the convex lens to about 440 mm in front of the illuminated source and repeat steps 4 – 10 and fill out row 2 in Table 5.
13. The three values of the focal length should be approximately the same. To measure how well they agree, calculate the average value and a percentage discrepancy.

$f_{average}$ = ______ mm

Discrepancy = ______ %

14. A value of the magnification m_d calculated from d_o and d_i should be very close to the corresponding value of m_h calculated from h_o and h_i. To see how accurate that is, complete Table 4 using the following formulae.

$m_{average} = ½(m_d + m_h)$

	$m_{average}$	*Discrepancy*
First Measurement		%
Second Measurement		%
Third Measurement		%

Table 4