Lenses and Optical Instruments

Introduction and Theory: Text reference: Young, Adams, and Chastain §24.5

When a light ray passes through an interface of two media with different indices of refraction, it changes direction according to Snell's law. Lenses are optical devices that make full use of this property.

There are two ways of analyzing how a lens works. One is with the thin lens formula and the magnification formula:

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

$$m = \frac{h_i}{h_o} = -\frac{d_i}{d_o} \tag{2}$$

In the above formulas d_o is the object-lens distance, d_i is the image-lens distance, f is the focal length of the lens, h_o and h_i are the heights of the object and the image, and m represents the magnification. By sign convention d_o is always positive, d_i is positive if the image is formed on the opposite side of the lens from the object and the image is real. A negative value for the d_i means that the image is on the same side of the lens as the object and the image is virtual.

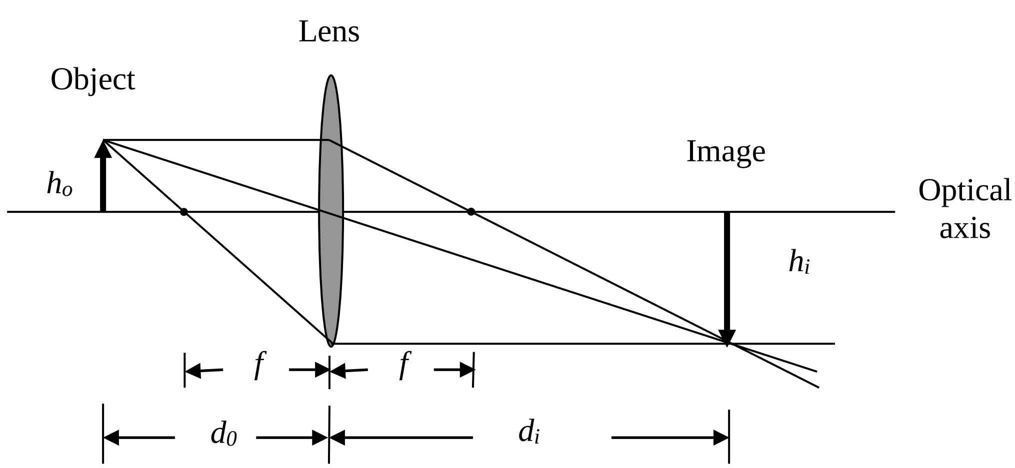


Figure 1. The ray diagram for a real image produced by a convex lens.

The value of f is positive for a converging lens. A positive magnification m means the image is virtual and erect; a negative magnification m means the image is real and inverted.

The other method of lens analysis is the ray-tracing diagram. To construct an image one has to consider the following three rules:

1. any light ray which is parallel to the optical axis, upon reaching the lens will pass through the focal point of the lens on the image side;

2. any light ray which passes through the center of the lens, will continue straight through to the image side of the lens (this ray is undeviated because it makes the same angle with the glass on both sides of the lens);
3. any light ray, which passes through the focal point on the object side of the lens, will travel parallel to the optical axis into the image side of the lens.

Figure 1 shows an example of constructing the image for a positive (convex) lens when the object is located farther from the lens than the focal point ($d_o > f$).

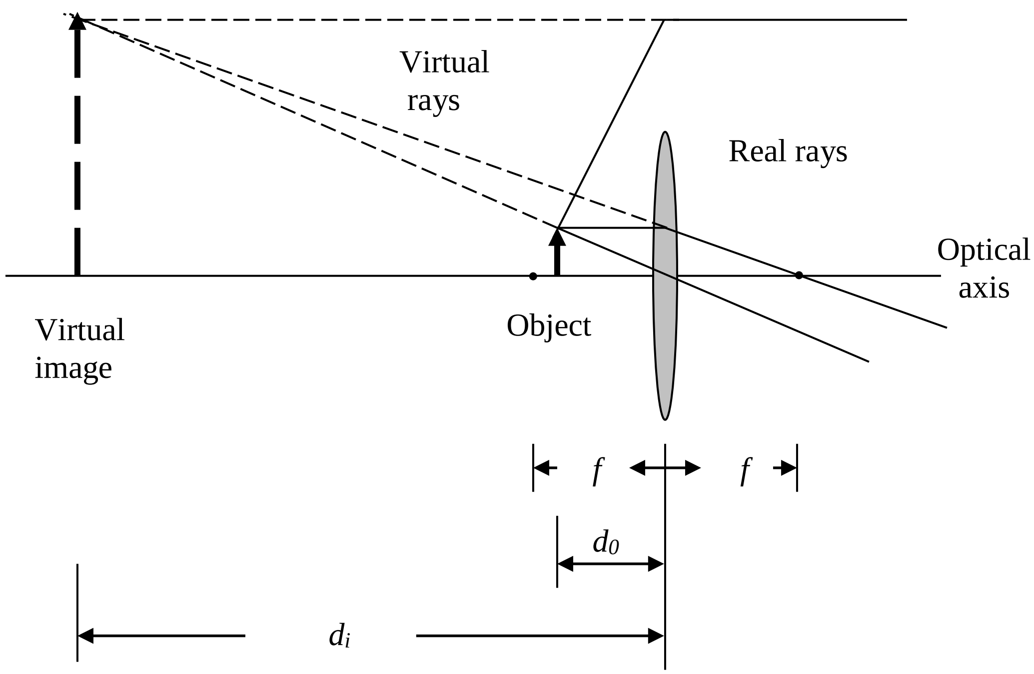


Figure 2. The ray diagram for a virtual image produced by a convex lens.

Figure 2 gives the ray-tracing diagram for the situation with a positive (convex) lens and the object located closer to the lens than the focal point ($d_o < f$). In this case the three traced rays diverge on the right side of the lens. Thus they **appear** to come from a "virtual" image on the same side of the lens as the object.

Figure 3 is a ray-tracing diagram for a compound microscope. D represents the distance between the objective lens and the intermediate image. It is called the tube length of a microscope. The objective lens produces a real intermediate image of the original object, which in turn serves as an object for the eyepiece. The eyepiece acts as a magnifier and forms a virtual image, inverted with respect to the original object. The overall magnification of the microscope will be the product of the magnification of the objective lens and the magnification of the eyepiece:

$$M = M_{obj} \times M_{eye} \quad (3)$$

The magnification of the objective M_{obj} can be determined approximately as D / f_{obj} (or from the real distances or sizes as in the lab). For a simple magnifier the magnification of eyepiece M_{eye} is given by $(N / f_{eye} + 1)$, where N is called the near point. For a normal eye N has an average value of 25 cm. So a lens with a focal length of 2.5 cm will be an $11\times$ magnifier.

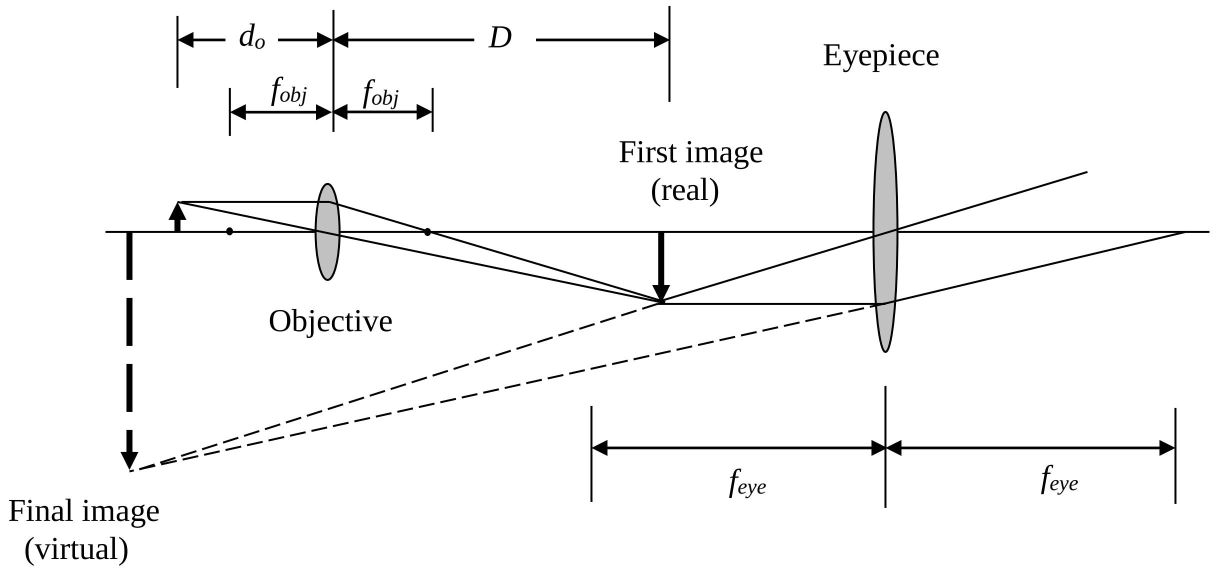


Figure 3. Ray-tracing diagram for a compound microscope.

Good microscopes use complicated multi-lens units for both the objective and the eyepiece in order to obtain high magnification and quality images.

Objectives:

To explore the optical properties of a thin lens; to determine the focal lengths of positive lenses from real and virtual images; to construct the compound microscope.

Equipment:

Optical bench with accessories, 2 convex lenses, light source, mounted reticle with markings spaced 0.1 mm, ruler.

Procedure:

A. <u>Determining the approximate focal length for each lens</u>.

On the lab table form the image of a light source that is a long distance away ($d_o \sim \infty$) such as a far light fixture on the ceiling. The distance from the lens to the table will be approximately the focal length because 1/infinity is approximately zero.

B. <u>Determining the focal length from a real image.</u>

As the object in this experiment use the markings on the screen in front of the provided light source. Set up the optical bench in the fashion depicted in Figure 4.
Make sure that the lighted object is more than 4 focal lengths from the ground glass screen where the image will be formed. Adjust the height of all three elements so they are at the same level. Find the position of the lens corresponding to a clear and crisp image of the object.

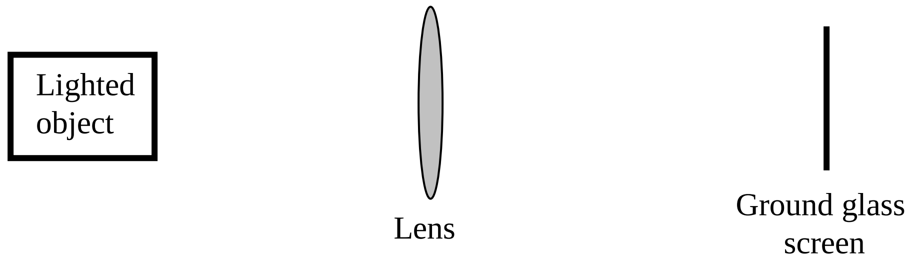
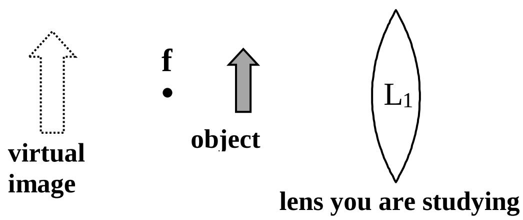


Figure 4. Arrangement of equipment for measurements of focal length of lens with real images.

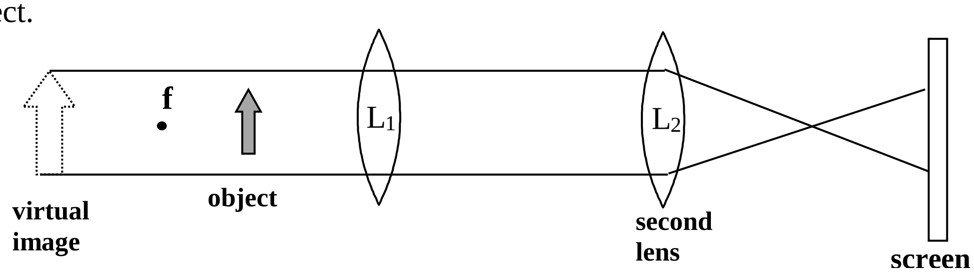
Record all distances and use equation (1) to calculate the focal length. Measure the size of both the object and the image, and calculate the magnification. Re-adjust the lens position for another location delivering a new good, sharp image and repeat all measurements. Follow the same procedure for the other lens.

C. <u>Determining the focal length from a virtual image.</u>

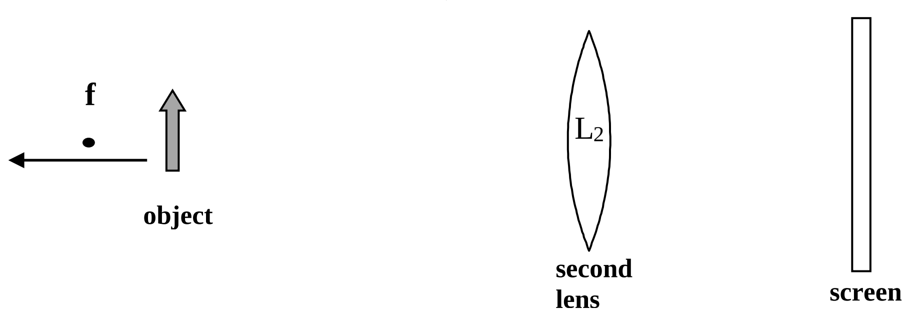
Step 1: Place the object inside the focal length of your convex lens. For this set-up use the **short** focal length lens. Of course an image will not be able to focus on your screen as the image formed is virtual.



Step 2: Place a second convex lens to the right of the first. A focal length from 15-20 cm works well. Adjust the second lens and screen until you get a nicely focused image on the screen. (The larger the image the better.) The image you see is there because the second lens is using the virtual image of the first lens as its object.

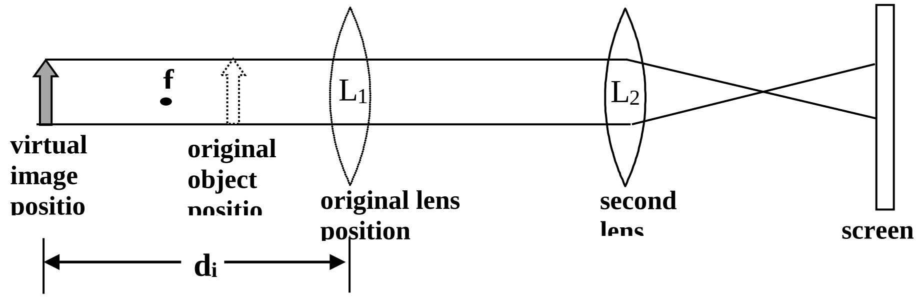


Step 3: Note the position of the first lens and then remove it. Do not touch the second lens or the screen



Step 4: Move the object to the left until a focused image appears on your screen. The object is now in the same location as the virtual image from the first lens. The distance from the original lens position to

the new position of the object is the image distance for the virtual image from step 1.



D. Constructing a compound microscope.

Follow the set-up shown in Figure 6 leaving out the ruler. As the objective lens use the short focal length lens. For the object use the small etched scale called reticle, which is mounted at the end of a metal tube. This reticle has major numbers every mm and small markings spaced 0.1 mm. The ground glass is added to diffuse the light.

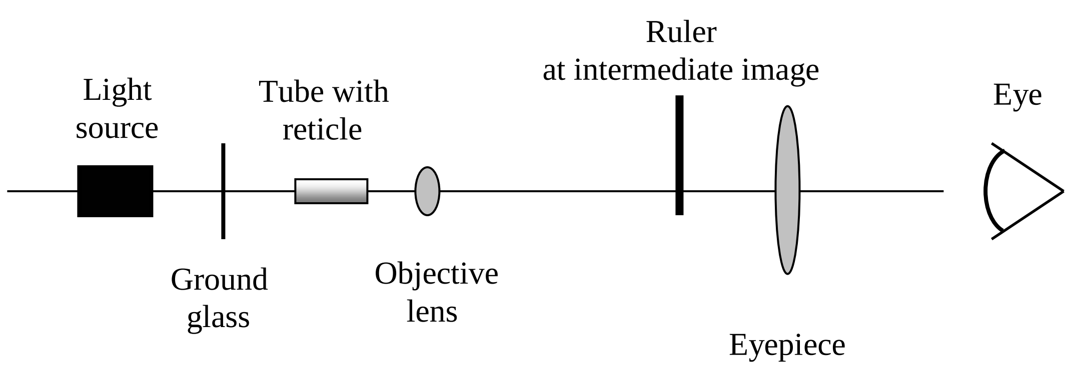


Figure 6. Schematic arrangement of equipment for a compound microscope.

Focus lenses so that you can see an enlarged view of the reticle in the eyepiece. Now add the ruler and find the location of the intermediate image – when moving your head slightly right and left you should see the image of the ruler and the image of the reticle moving together.
Find the total magnification of your compound microscope. Hint: The magnification of the objective can also be calculated as the ratio of the size of the reticle read on the ruler image seen in the eyepiece to the image of the reticle observed in the eyepiece.

Final conclusion:

Tabulate neatly all measured and calculated parameters. Did the experiment prove the theoretical predictions on thin lenses?

Self-assessment questions:

1. Where is located the real image relative to the object and lens?
2. Where is located the virtual image relative to the object and lens?
3. Is the magnification positive or negative for the real image?
4. Is the magnification positive or negative for the virtual image?
5. What the right formula for the convex lens if the image is real?
6. What the right formula for the convex lens if the image is virtual?