General Physics Lab 9

Image Formation by a Thin Lens

Objectives:

- To observe the imaging properties of a thin lens including the lens equation and magnification

Equipment:

- Converging Lens (10 cm < f < 20 cm)
- Modeling Clay
- Aluminum Foil (15 cm x 15 cm)
- Stiff Black Paper (can use leftover conductive paper)
- Light Source (desk lamp, lamp, large flashlight, etc.)
- Index Card
- Triangular Wood Block
- Measuring Tape
- Ruler
- Scissors
- Tape

Physical Principles:

Converging Lenses

A converging lens has a focal point on either side of the lens – the primary focal point, F, and the secondary focal point, F'. Light originating from an object at infinity approaches the lens in rays parallel to the optical axis and converges at the secondary focal point, F' (see Fig. 1a). In reversible fashion, light rays originating from the primary focal point, F, will emerge from the lens in rays parallel to the optical axis and will not converge to form an image (see Fig. 1b). The focal length, f, is the distance from the thin lens to either focal point, F or F'.

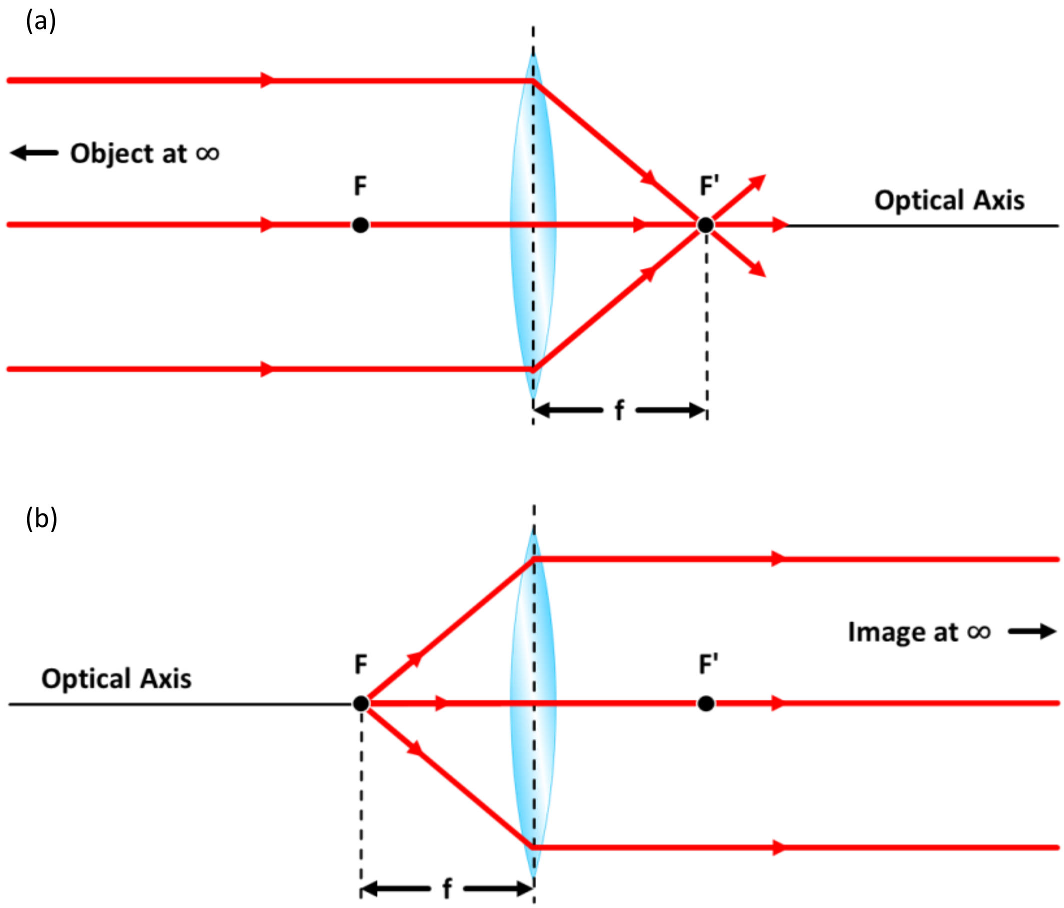

Fig. 1: Ray traces for a converging lens. (a) Light from an object at infinity (s = ∞) approaches the lens in parallel rays and is bent to form an image at the secondary focal point (s' = F').
(b) The lens bends rays from an object at the primary focal point (s = F) into parallel rays (s' = ∞).

Thin Lens Equation

An object located at an arbitrary object distance, s, will have the corresponding image form at image distance, s' (see Fig. 2). The relationship between s and s' is given by the lens equation.

$$\frac{1}{f} = \frac{1}{s} + \frac{1}{s'} \qquad (1)$$

Convince yourself that Eq. (1) implies that if s = ∞, s' = f and if s = f, s' = ∞.

Fig. 2 illustrates ray traces for an object located at a distance s > f for a converging lens. Ray 1 approaches the lens parallel to the optical axis and thus converges to the secondary focal point F'. Ray 2 approaches the lens through the primary focal point, F, and emerges from the lens parallel to the optical axis. Ray 3 passes through the center of the lens and is unaffected by the thin lens. The convergence of these three rays forms the location of the real, inverted image at s'.

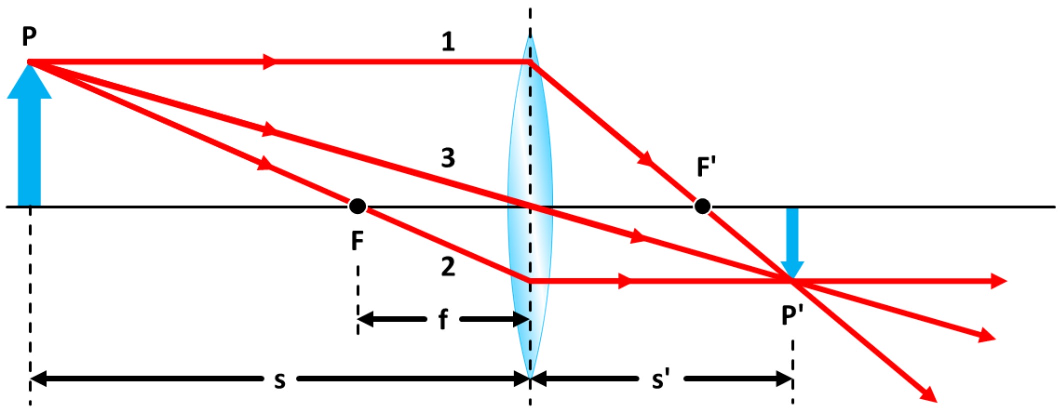

Fig. 2: Ray traces for an object (P) located at object distance, s > f, in front of a positive lens of focal length, f. The rays converge to form a real, inverted image (P') at the image distance, s'.

Lateral Magnification

As shown in Fig. 3, the lateral magnification, m, of a lens is given by,

$$m = \frac{y'}{y} = -\frac{s'}{s} \quad , \tag{2}$$

where y is the object height and y' is the image height. If the image is inverted, y' is negative.

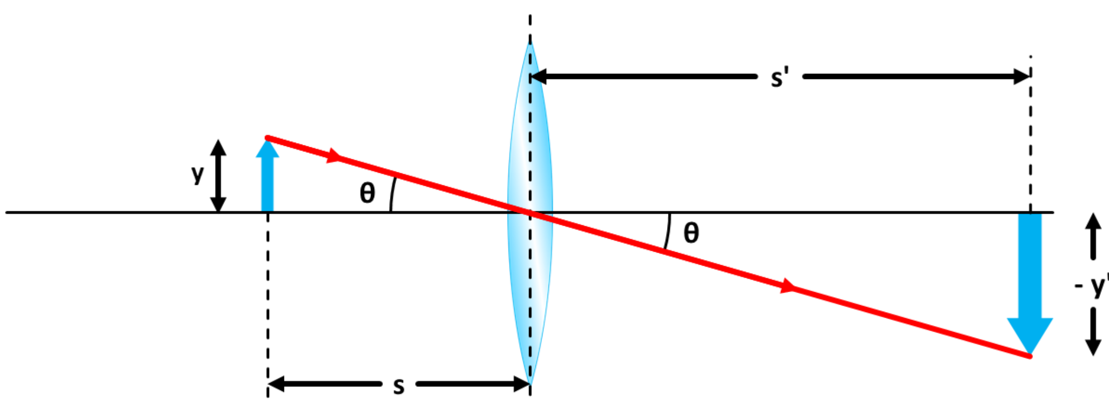

Fig. 3: An object of height, y, forms an inverted image of height, -y'.
Similar triangles give a linear magnification of $m = \frac{y'}{y} = -\frac{s'}{s}$ for this inverted image.

Procedure:

Make Lens Holder

1. Form a block of clay about 5 cm x 2 cm x 1 cm (see Fig. 4a).
2. Squish the middle of the long side down and draw the edges of the long side up to form a U-shape trough a little narrower than the diameter of your lens (see Fig. 4b).
3. Wrap the upper part of the clay in aluminum foil to keep clay off the lens (see Fig. 4d & 4e). Keep the bottom of the clay unwrapped to remain somewhat sticky.
4. Press the lens down into the foil-covered U and squeeze the foil/clay up around the edges of the lens to hold it securely in an upright position (see Fig. 4f). Fig. 4g shows what the clay and foil would look like if the lens were removed (don't actually remove your lens, this is only for illustrative purposes). When handling the lens, try to hold it on the edge to keep the main surfaces clean.
5. Last, draw/mark a line down the side of your lens holder to indicate the edge of the lens (see Fig. 4h). This makes it easier to align the lens with the measuring tape when measuring distances.

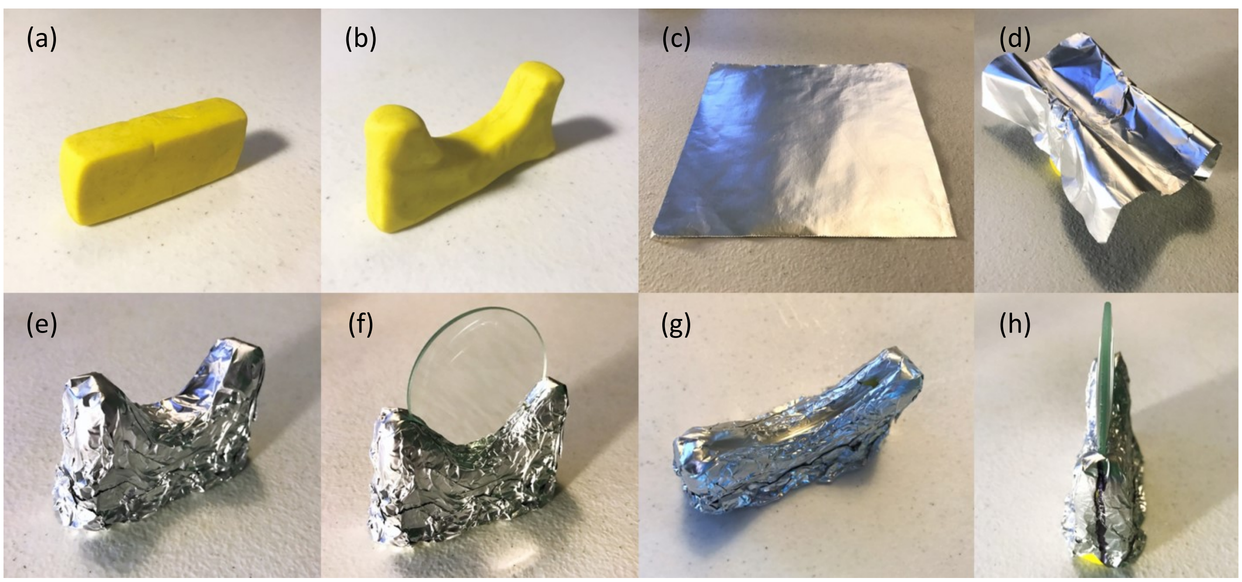

Fig. 4: Make a lens holder by (a) forming a block of clay and (b) squishing it down in the middle and up on the sides to make a U-shape. (c) Take a small sheet of aluminum foil and (d, e) form it around the clay. (f) Insert the lens and squish the clay and foil in around it. (g) Underneath the lens, it should look like this with a groove formed in the clay and foil. (h) Draw a line down the side of the holder. This will be used for alignment when measuring distances.

Make Image Screen

1. Use Scotch tape to attach an index card vertically to the triangular wood block from 1st Semester (see Fig. 5).
2. Orient the card so that the blank (un-lined) side faces away from the wood (see Fig. 5b).
3. Notice in Fig. 5b that the bottom edge of the card is slightly elevated above the table surface to make it easier to slide the screen across the table.

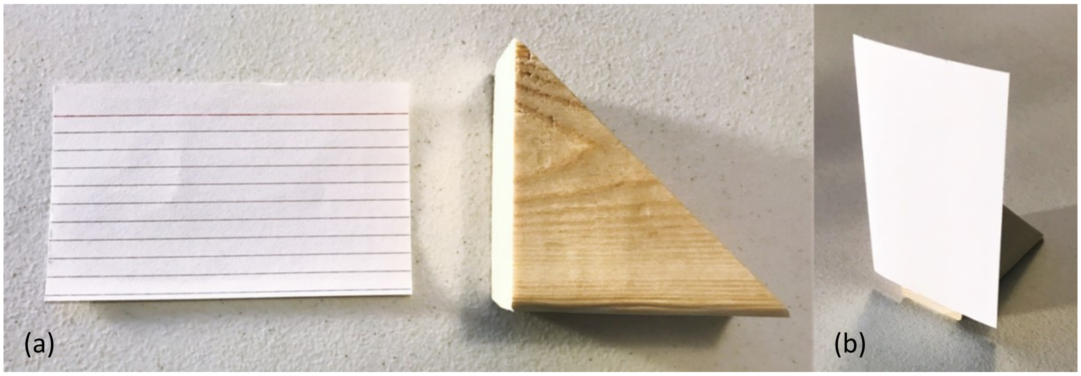

Fig. 5: Make a screen by taping an index card (blank side out) to the triangular wood block.

Make Object

1. Cut a square of stiff black/dark paper about 12 cm x 12 cm (see Fig. 6a). You can use your own paper or some of the conductive paper from the earlier labs.
2. Fold the paper in half (black side out if you used conductive paper) and cut out half of a small arrow or triangle shape. It should be close to the bottom edge of the paper and about 3 cm tall (see Fig. 6b).
3. When you unfold the paper, it should be able to stand up, and the pointed end of the arrow/triangle should be at about the same height as the center of the lens.

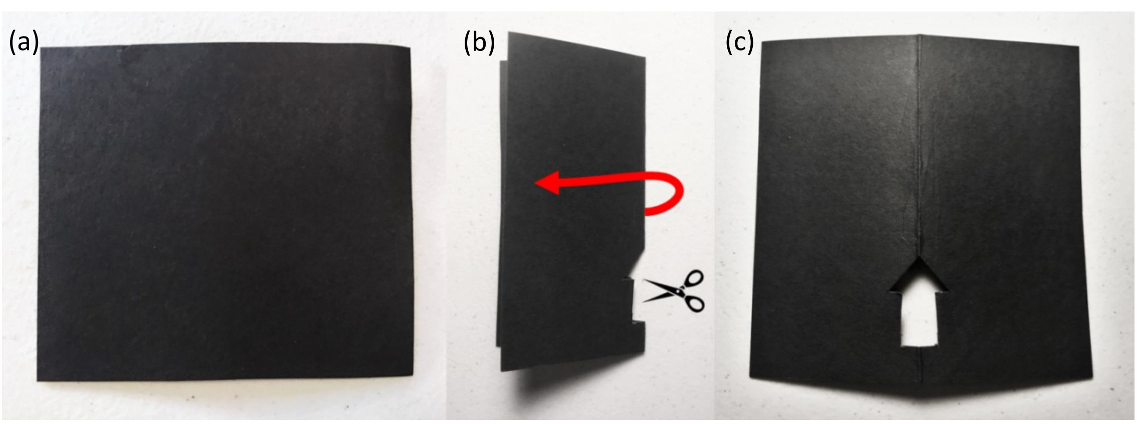

Fig. 6: Make an object from a piece of dark paper. (a) Fold the paper in half and (b) cut a small arrow or triangular hole near the bottom of the paper (same height as center of lens). (c) Partially unfold the paper so that it can stand up on a flat surface.

Measure Focal Length

1. Find a reasonably large room and turn off the lights.
2. Place a desk lamp or large bright flashlight across the room from the lens (at least 5 or 6 meters away), and arrange your lens and screen such that the light crosses the room, passes through the lens and converges on the screen. Alternatively, you may allow daylight from a window to fall on the lens/screen and focus on distant objects outside.
3. Adjust the screen distance from the lens to get a sharp image of the light source (see Fig. 7a-c).
4. Use a ruler or measuring tape to determine the distance between the lens and screen (Fig. 7d). Record this distance as the measured focal length.

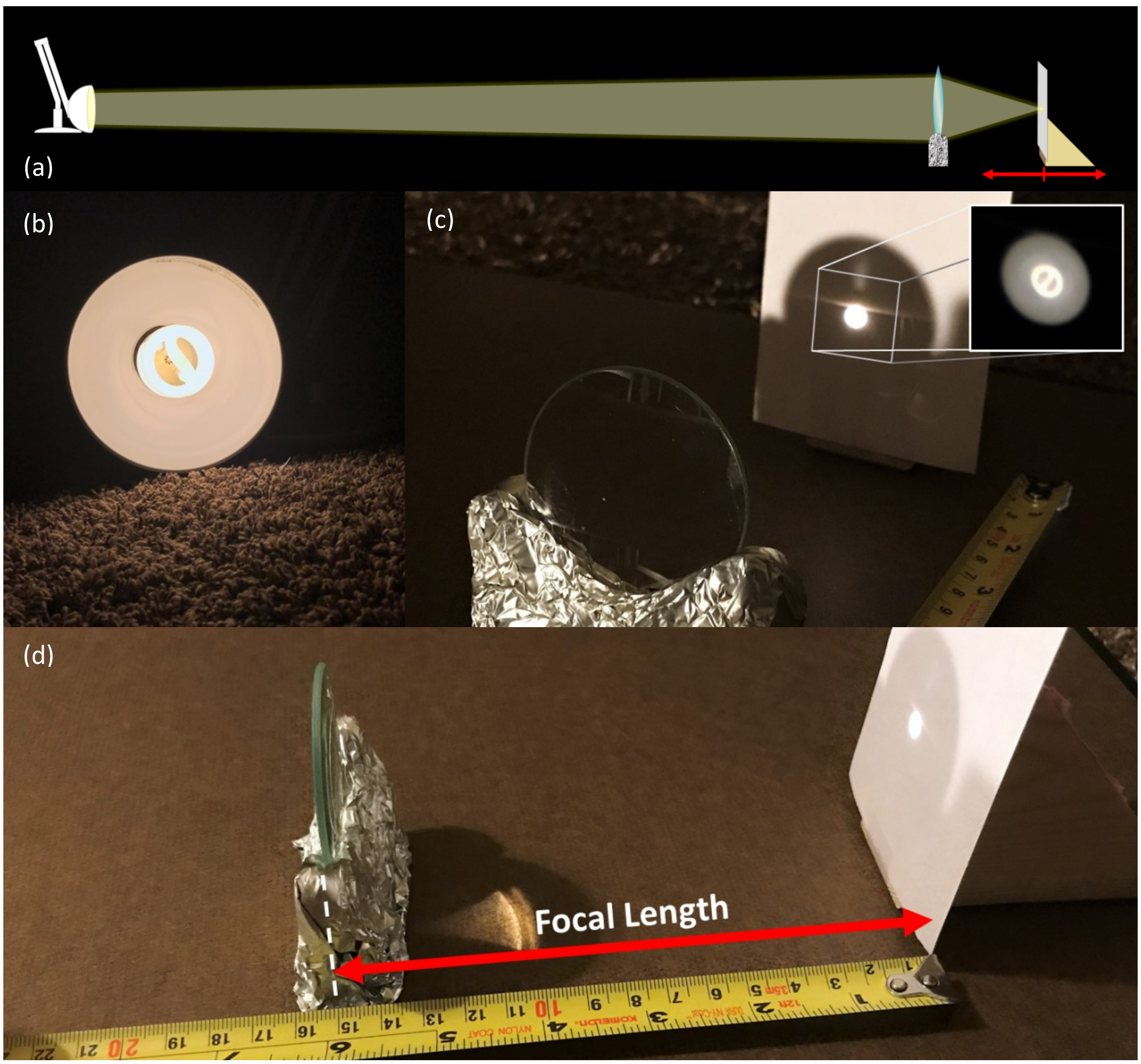

Fig. 7: (a, b) Shine a distant light source through the lens onto the screen. (c) Adjust the screen position to achieve a sharp focus of the light source (easier to see in person). (d) Measure the distance from the screen to the center of the lens and record it as the focal length.

Thin Lens Equation

1. Set the light source, arrow object (dark side facing lens), lens, and screen on a table or other flat, level surface. Arrange them all in a straight line as shown in Fig. 8.

   When you set up the object paper, try to unfold it as much as possible without it falling over. If the paper is bent too much, or if the hole is too large, the front and back edges of the hole will not be in focus together, and this will make the next steps difficult. Set it on a firm flat surface to help it stand up.

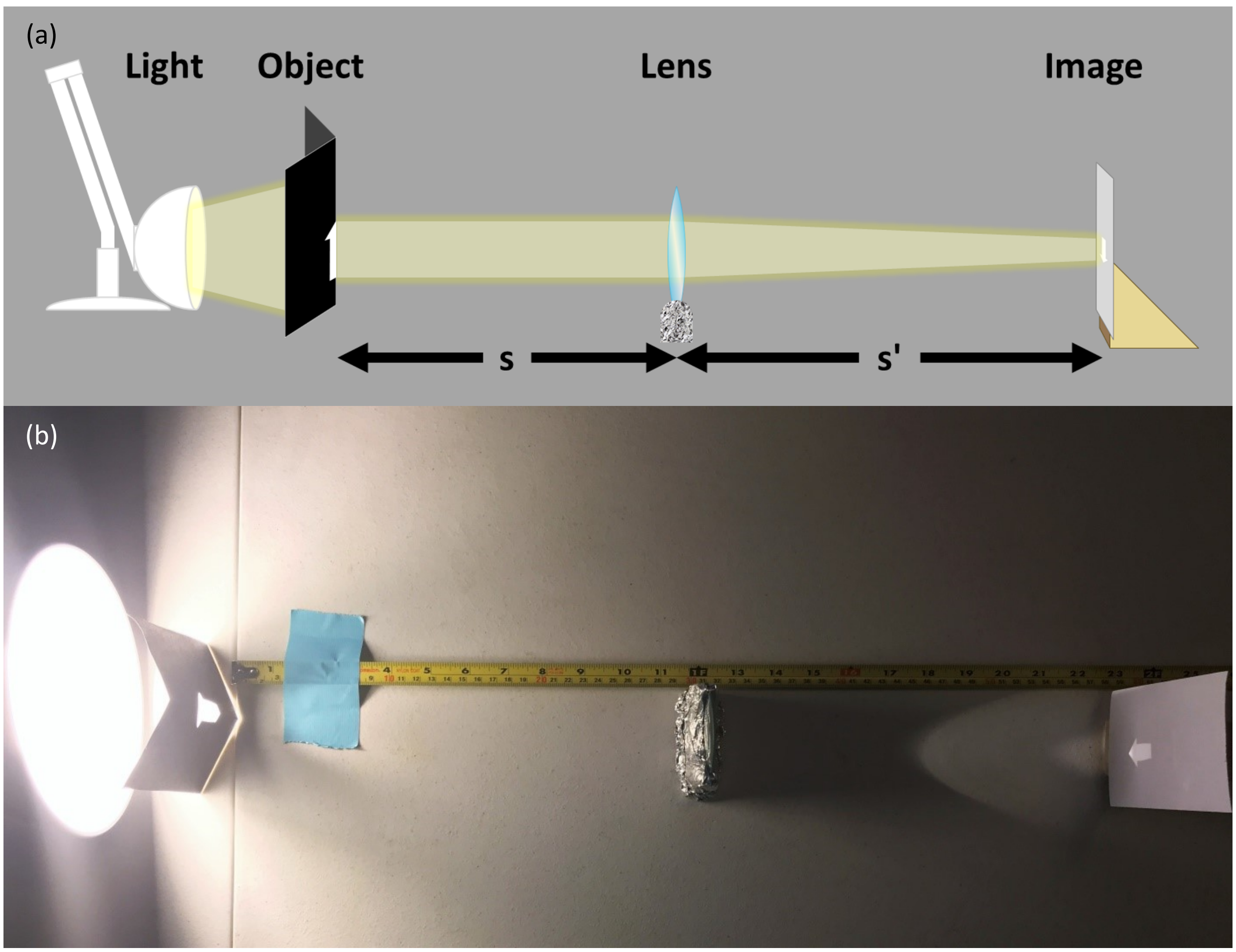

Fig. 8: Set the light source, object, lens, and image screen all in a row on a flat, level surface. Use the tape measure to set the object distance, s, and measure the image distance, s'. Measure the object distance from the front or middle of the object hole to the center of the lens. Measure the image distance from the center of the lens to the screen. Measurements to the lens may be easier if you use the line drawn on the holder (Fig. 4h).

2. Use a measuring tape to set the object distance, s, to f + 5 cm, and record this distance. For example, if your measured focal length is 10 cm, set the object distance to 15 cm, if the focal length is 15 cm, set the object distance to 20 cm, etc. This is because no image forms at the primary focal point so we need to avoid that distance.
3. Adjust the image screen position to achieve a sharply focused image.

Troubleshooting Tips:

If you have a hard time telling where the image is in focus, you might try the following.

- Use the lens equation (Eq. 1) to predict the image distance. Then adjust the screen position around this distance to find the best focus.
- Flatten the object paper more so that all of it will be in focus together.
- Do not use a light source that is smaller than the object hole (i.e. smartphone flashlight). Instead, use a light source that is larger than the hole (light bulb, lamp, etc.).
- Make sure the object hole, lens center, and screen are all in a straight line, and the image is not forming above/below the screen.

4. Measure and record the image distance, s'.

   Note: If you choose to tape down the measuring tape, as in Fig. 8b, then the image distance, s', would be the screen position (distance from object to screen) minus the lens position (distance from object to lens). However you choose to measure s and s' is fine, as long as it represents the distances shown in Fig. 8a.

5. Increase the object distance by about 5 cm, adjust the screen to focus the image, and record the new object and image distances. Notice that the larger the object distance, the smaller the image distance.
6. Continue increasing the object distance by 5 cm each time until you have recorded at least 6 sets of measurements with object distances ranging from about f + 5 cm up to around f + 30 cm.

Lateral Magnification

1. Set the object distance to 40 cm and adjust the screen to achieve a sharp image.
2. Record the object distance (s = 40 cm) and image distance (s' will depend on the focal length). Alternatively, if you read this section before completing the thin lens equation measurements, you can do these measurements at the same time.
3. Measure the height of the inverted image on the screen, y' (see Fig. 9a). Note that because the image is inverted, the height, y', must be recorded as negative.
4. Measure the height of your arrow/triangle object, y (see Fig. 9b).

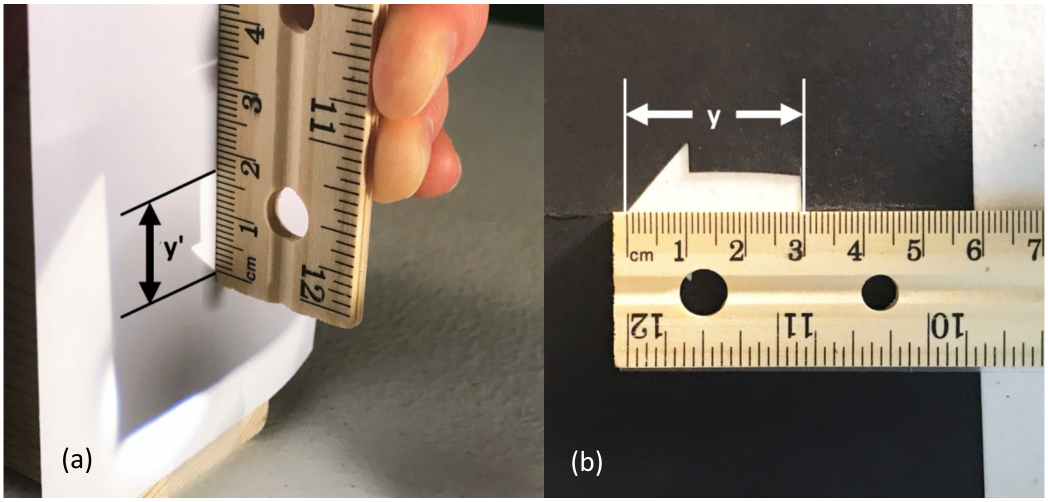

Fig. 9: (a) Measure the image height, y'. (b) Measure the object height, y.

Analysis:

Thin Lens Equation

Eq. (1) may be rearranged as follows:

$$\frac{1}{s'} = -\frac{1}{s} + \frac{1}{f} \qquad (3)$$

By comparing Eq. (3) to the equation of a straight line (y = mx + b), we can see that a plot of 1/s' vs. 1/s should yield a straight line with a slope of -1 and a y-intercept of 1/f.

1. Generate a plot of 1/s' (y-axis) vs. 1/s (x-axis).
2. Apply a linear fit and record the slope, m, and inverted y-intercept, 1/b.
3. Compare the slope, m, to -1 using a percent error.

$$\%Error = \frac{|(-1) - slope|}{|-1|} \times 100\%$$

4. Compare the inverted y-intercept, 1/b, to the measured focal length, f, using a percent difference.

$$\%Diff = \frac{\left|f - \left(\frac{1}{b}\right)\right|}{f} \times 100\%$$

Lateral Magnification

1. Calculate the predicted magnification, m_{pred}. The magnification should be negative because the image is inverted. Both distances, s and s', are positive.

$$m_{pred} = -\frac{s'}{s} \qquad (4)$$

2. Calculate the measured magnification, m_{meas}. The magnification should be negative because the image is inverted. Remember that y' is negative and y is positive.

$$m_{meas} = \frac{y'}{y} \qquad (5)$$

3. Compare m_{meas} to m_{pred} using a percent difference.

$$\%Diff = \frac{|m_{pred} - m_{meas}|}{|m_{pred}|} \times 100\%$$