Geometrical Optics

CAUTION: Never look directly into the laser beam, and do not position the beam so others will be looking at it! Be careful when using reflective materials around the laser to prevent accidental exposure by reflection.

Reflection from a Surface

Adjust the laser ray box so it emits a single ray of light. You can do this by changing the orientation of the bracket-shaped mask that comes with the box. Place the flat mirror in the beam at an arbitrary angle with respect to the beam. (To facilitate your measurements, you place a sheet of paper under the setup and trace the ray and mirror locations.) Find the normal to the surface with the protractor provided. Determine the incident ray and the reflected ray angles. Use your judgment to estimate uncertainties. **Is the law of reflection confirmed?**

Mirrors that Act Like Lenses

We can take advantage of the law of reflection to construct a mirror that acts like a lens, with the ability to collect light and form an image.

Adjust the mask for your light box so that it emits a set of three parallel rays. Place the curved mirror in the beams with the concave side facing the incoming rays. Adjust the orientation such that the reflected beams are focused on the center incoming ray. Trace the rays and the mirror location.

The point of convergence of the reflected rays lies at the *focal point* of the mirror, and for this case, a *real* image is formed.

(Note: A curved mirror will not always form an image at its focal point. You are looking at a special case. Under other circumstances, the image will form at a different location from the mirror.)

Measure the distance between the focal point and the center of the mirror. This is the *focal length* of the mirror. Using a compass, also estimate the radius of the mirror. **How does the focal length compare to the radius of curvature of the mirror?**

Now place the mirror in the beam with the convex side facing the incoming rays. Trace the rays and the mirror location. Note that the beams do NOT converge, and that for this case a *virtual* image is formed.

Extend the reflected rays back "behind" the mirror to find the location of the focal point of the virtual image. Measure the distance from the mirror to this point. Using a compass, also estimate the radius of the mirror. **How does the focal length of the convex side compare to the radius of curvature of the mirror?**

Reflection and Refraction from a Surface

Adjust the ray box mask so that it projects a single beam into the rectangular block. *To facilitate your measurements, you may draw the rays on the paper, but* ***please***

do not leave ink or pencil marks on the clear block. Determine the incident ray and the refracted ray angles. **What is the index of refraction of the clear block material?**

Total Internal Reflection

We have seen how at each optical boundary, part of the incoming light beam is reflected and part is refracted. However, if certain conditions are met, we can have **total internal reflection** with no transmission through the interface.

Two conditions must be met:: first, n_2 (the medium containing the *incoming* beam) must be greater than n_1, and second, the angle of the incoming beam must be greater than or equal to the critical angle, such that:

$$\sin\theta_{critical} = n_1/n_2$$

Shine a single beam through the half disk, triangle, or trapezoid block. Rotate the block to observe the transition angle between total internal reflection and partial internal reflection. This transition occurs at the critical angle, $\theta_{critical}$. Measure $\theta_{critical}$ and compute the index of refraction for the material. **Do you think this block and the rectangular block are made of the same material?**

Refraction of Light – Lenses

Adjust the light ray box so it emits the three center parallel rays of light. Take the convex lens and place it on a piece of paper in front of the light box. The frosted side of the lens should be facing down. If this is the case, the rays will be visible as they pass through the lens. Trace the outline of the lens, as well as the incoming and outgoing rays on the graph paper. Observe how the rays are refracted at both the front and back surfaces of the lens.

On the paper, extend the outgoing rays until they meet. This is the focal point. This is also a *real* image, since the light rays really converge. And so this lens is also known as a *converging* lens. Measure the focal length, f, from the midline of the lens to the focal point.

(Note: A lens will not always form an image at its focal point - this is a special case. We will investigate more general cases later.)

Now, repeat the above procedure (i.e., find the focal length) for the concave lens. Since the outgoing rays diverge, you must extend the diverging rays backwards to find the focal length f. It is customary to draw in these imaginary rays with dotted lines to indicate that where they cross is where an image *appears* to form. This is called a *virtual* image, and the focal length and radius of curvature are given as negative numbers to indicate this. Since the outgoing rays from the lens diverge, this is also known as a *diverging* lens.

The Thin Lens Equation

The thin lens formula is

$$\frac{1}{\ell} + \frac{1}{\ell'} = \frac{1}{f},$$

where ℓ and ℓ' are the object and image distances, respectively, and f is the focal length of the lens.

This formula is general for converging and diverging lenses and for any location of the object with respect to the lens if the numerical values assigned to the algebraic symbols are given signs in accord with the following sign convention:

f	+ for converging,	- for diverging
ℓ, ℓ'	+ for real,	- for virtual

You should be aware that some books use a different sign convention, in which case some of the signs may be reversed! This lab will adhere to these conventions.

An important special case occurs when the object is at infinity. In this case, all the incident rays from an object point are parallel to each other, and the image is formed at the focal point. You can see this by substituting $\ell \to \infty$ into the formula.

Converging Lenses and Real Images

1. Determine which of your three optical bench lenses are converging and which are diverging. One way to do this is to look through the lens at a far away object (use the hallway!). A converging lens produces an inverted image when it is held at arm's length.
2. Set up the ground glass within a few centimeters of the end of the meter stick nearest to you. Use an object located as far away as possible, take each of the two converging lenses in turn, and move the lens to focus sharply on the ground glass (observe the image by looking at the ground glass from the back). Predict which forms the larger image, the long or short focal length lens? Why?
3. Determine the distance between the lens and the object using a tape measure. (Measure as precisely as you can, and estimate your uncertainty). You can determine the distance from the lens to the image (ground glass) using the markings on the optical bench. Repeat for the other converging lens and calculate the focal length of each.
4. **Error analysis.** Find the uncertainty in f, using your techniques for propagation of uncertainty. There is also a shortcut: when ℓ is much larger than f, the image is very nearly at the focal point ($\ell' \approx f$) and the computed f is not much influenced by ℓ. It follows that the uncertainty of the focal length is essentially equal to the uncertainty of the measured image distance. See if you can convince yourself of this!

Q3. Which lens produced the larger image: the longer or shorter focal length?

Record ℓ, ℓ', and f (with uncertainties) for each of the converging lenses.

Diverging lenses and virtual images

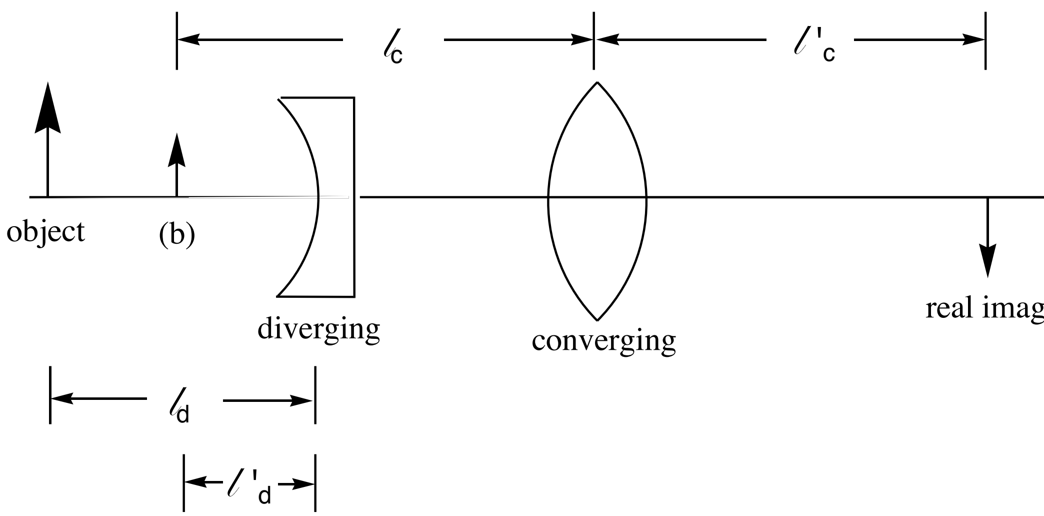
1. With a real object, a diverging lens can only produce virtual images, so you can't measure the focal length of your diverging lens by catching its image on a ground glass screen. Convince yourself this is true by placing the diverging lens in the lens holder on the optical bench and try to get an image on the ground glass.
2. So, what do we use diverging lenses for? One use of a diverging lens is to correct nearsightedness. Take your diverging lens off the meter stick. Now let's make a simple model of your eye by placing the short focus converging lens on the meter stick with the ground glass about 20 cm from one end of the bench. Use an object at the other end of

the bench. As you did earlier, get a focused image onto the ground glass. Here, the converging lens acts like the lens of your eye and the ground glass acts like your retina.

3. Nearsightedness is caused by a distortion of your eye that causes the image formed by the lens to be focused at a point in front of the retina. Now, simulate this by moving the ground glass away from the converging lens by approximately 15 cm.

4. Next, place the diverging lens approximately 15 cm in front of the converging lens. This diverging lens will act like a corrective lens. **Move** the diverging lens slowly back and forth until you get a focused image. Now you have corrected vision!

5. Now, lets see if we can find the focal distance for the ***diverging*** lens (f_d) by using our lens equation and making a few measurements.



6. You already measured f_c (focal length of converging lens). **Measure** ℓ'_c, and use f_c and ℓ'_c to calculate ℓ_c from the thin lens equation. Notice, from the above illustration, that the image formed by the diverging lens, (b), is the *object* for the *converging* lens, i.e. the converging lens "sees" (b), not the original object.

7. **Measure** ℓ_d (object distance for *diverging* lens) and **find** ℓ'_d. Use ℓ_d and ℓ'_d in the thin lens equation to find f_d.

8. What is the precision of your determination of the focal length by this rather indirect method? There are two contributions to error: the focal length of the converging lens, and the position adjustment to give sharpest focus. It's a pain to do the error propagation in a formal way. We will give you an approximate shortcut: Take the uncertainty in f to be about three times your experimental uncertainty in locating the position of the best focus.

<u>To Include in Your Notebook</u>:

Sketches for concave and convex lenses

Answers to questions, including all measured and calculated values