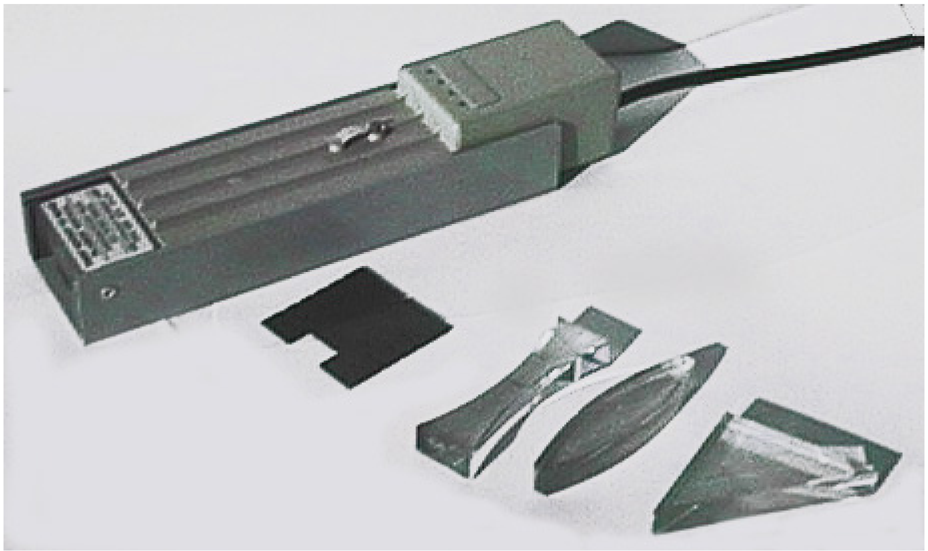
Ray Tracing

Introduction: The path light travels through space and other various media gives a clue to how lenses and mirrors work. We will follow the progress of a series of light beams as they encounter optical devices by tracing **all** the incident and reflected/refracted rays, as well as **all** the optical devices. A simple ray tracing apparatus, which emits rays of light, and various mirrors and lenses.

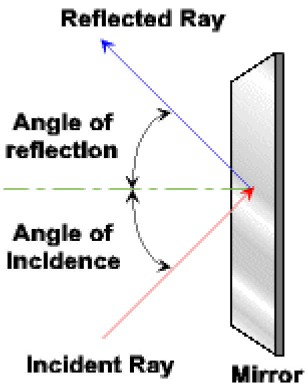


Light from a light bulb or a sun is isotropic, meaning the same in every direction. This apparatus allow us to use light that travels in only one direction.

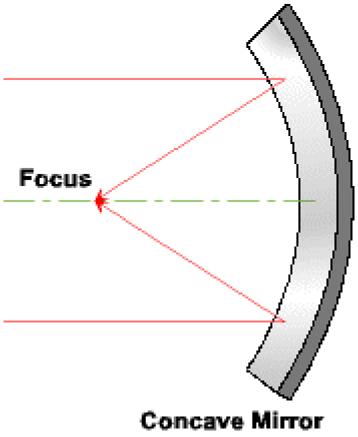
Theory: Light, indeed any electromagnetic radiation, has a dual existence: it has the properties of both a particle and a wave. Particles and waves have mutually exclusive properties; for instance, particles exist in a well defined space while waves are spread out over a wide area. Also, waves have a frequency but particles don't. (Modern Physics discussions actually contradict this). This duality allows us to use *either* aspect to trace light's path.

If we think of light as a jet of particles called *photons* we create a ray of light that travels in a straight line until it encounters an optical device like a mirror or lens. Using key points in the layout of these devices we can trace the path of a ray of light. This is called geometric optics. The key points are the optic axis (an imaginary line through the center of the lens or mirror), the plane of the device, and the focal point. From these three points we can position the image created by a lens or mirror.

The Details: Mirrors work because they reflect most of the visible radiation incident upon their surface. (There is always a combination of transmission and reflection at the interface of two media.) Suffice to say that the angle of incidence between the ray and the normal or perpendicular to the surface is equal to the angle of reflection, much like billiard balls without any spin striking the cushion.

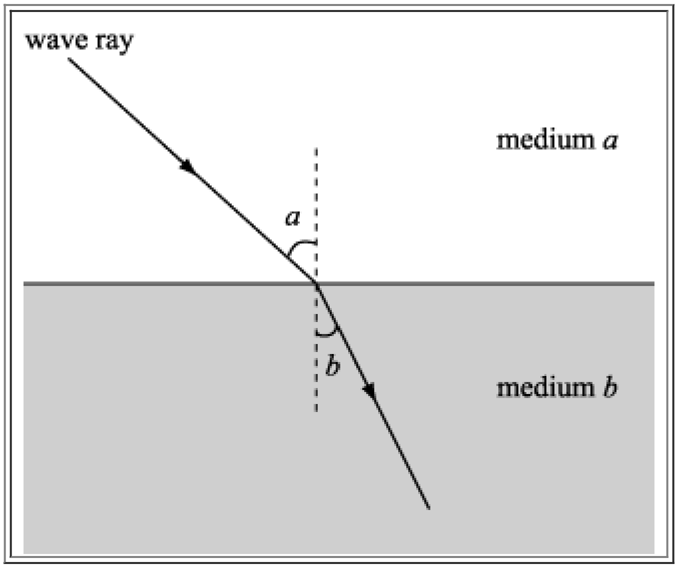


The incoming rays to a lens or mirror are called incident rays (subscript **i**) and the outgoing rays are reflected or refracted (subscript **r**). If the mirror is curved inward, called concave, or curved outward, called convex, the angle is made with respect to the normal where the ray is incident to the tangent of the surface. (A tangent line is a straight line that just touches the curve of a circle or a part of a circle, and these curved lenses and mirrors are arcs, sections of that circle.)

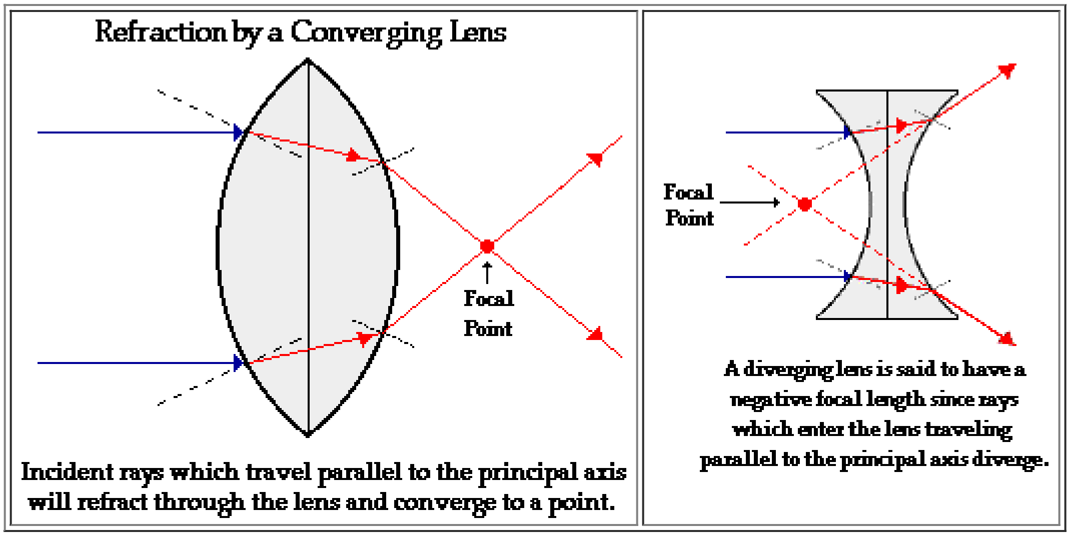


The image occurs where various reflected rays or their extensions cross.

Lenses work because they allow a significant amount (but not all) of the incident ray to penetrate and pass through their volume. But not without effect: the speed of light in space (or air) is $3X10^8$ m/s; however, because of the nature of lens material, light slows down inside. This causes the ray to bend relative to its direction of travel, unless it is perpendicular to the surface.



The oblique (non-perpendicular) ray bends toward the normal (or perpendicular) upon entering the lens, and bends away once it leaves. For a rectangular plate of glass the emerging ray travels a path parallel to the incident ray, but for glass curved inward (concave) or out ward (convex) rays are either diverged (spread out) by concave lens or converged (focused to a point) by a convex lens.


Refraction by a Converging Lens

Incident rays which travel parallel to the principal axis will refract through the lens and converge to a point.

A diverging lens is said to have a negative focal length since rays which enter the lens traveling parallel to the principal axis diverge.

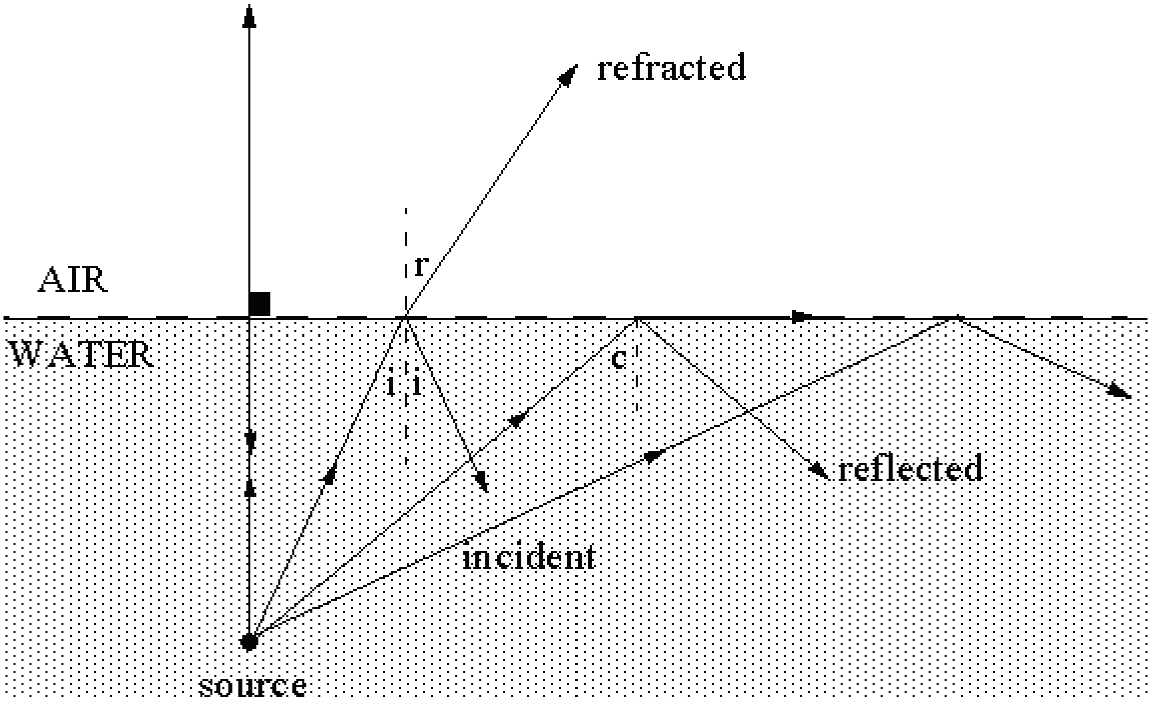
The ray tracing apparatus will produce a single beam or a series of parallel rays which will be affected by the mirrors or lenses placed in their paths. From the diagrams above, and from the ray tracings you will be able to locate two of the three key points on the optic axis: the focal point and the image distance. Using the fact that the focal length of a mirror is half the radius of curvature, the diameter of a spherical mirror can be determined.

The following equation is called the lensmakers' equation:

$$\frac{1}{f} = (n-1)\left(\frac{1}{R_i} + \frac{1}{R_r}\right)$$

where f is the focal length of the lens, R_i is the radius of curvature of the incident side, R_r is the radius of curvature for the refracted side, and n is the index of refraction. With careful tracing and measurement you will be able to find n for the lenses in this lab.

An interesting consequence of Snell's Law is the case of Total Internal Reflection. The maximum value of the sine function is 1. If $n_a > n_b$ the ratio of n_a over n_b is > 1. If a ray *inside* an optical device is incident on the exit surface at some angle **C** beyond that which is limited by the sine function, the ray will be completely reflected off the surface better than any mirror could reflect it. (*pretty technical, huh?*)



Task:

To verify the reflective properties of a plane mirror

To locate the focal point of a convex mirror

To find the radius of curvature of a concave mirror

To find the index of refraction of a double convex lens

To find the focal point for a concave lens

To find the critical angle for total internal reflection in a Plano-convex lens

Equipment:

- a ray projector
- three mirrors (two-in-one metal and plane)
- three lenses (convex, concave, and Plano-convex)
- protractor, straight-edge,
- lots of unlined paper. Use one sheet per drawing.

Procedure:

The general principle will be to aim the rays from the projector at various optical devices, tracing the paths of the rays, and recording critical measurements for later calculation. Use a separate piece of unlined paper under the rays for each phase of the experiment. Do this neatly as they will constitute the data for your experiment and report.

First, place the side of the black screen in the holder on the projector with the most slits face down. There is no on/off switch on the projector, so you'll have to plug/unplug it. **Adjust the length of the projector (by gently pulling is lengthwise) so that the rays emanating from the projector are**

parallel. For each experiment trace over the center ray to use as the optic axis. **Orient the mirrors and lenses similar to the figures above, and trace their outlines in each case.**

Flat Mirror

1) Place the single slit screen in the projector.

2) Place a plane mirror on the paper in such a way that the ray hits the mirror at an angle.

3) Trace the surface of the mirror on the paper.

4) Trace the ray from the screen to the mirror and along its reflected path.

Convex Mirror

1) Place the multiple slit screen in the projector. **Make sure your rays are parallel.**

2) Aim the rays at the convex metal mirror. They will diverge back toward the projector.

3) Trace the outline of the mirror on the paper.

4) Trace the incident and reflected rays.

Concave Mirror

1) Flip the metal mirror over so that the concave side faces the screen. **Make sure your rays are parallel.**

2) Aim the rays at the concave metal mirror. They will converge to the focal point of the mirror.

3) Trace the outline of the mirror on the paper.

4) Trace the incident and reflected rays.

Convex Lens

1) **Make sure your rays from your box are parallel.**

2) Use the lens to focus the rays to a point.

3) Trace the rays.

4) Trace the outline of the lens, just like you did with the mirror.

Concave Lens

1) Repeat the above steps for this lens.

2) Don't forget to trace the outline of the lens.

3) In this case the rays will diverge after they pass through the lens.

Plano-Convex Lens

1) Place the single slit into the projector.

2) Orient the Plano-convex lens so that the convex (not he flat one)surface faces the projector.

3) Trace the outline of the lens, including the flat side.

4) Slowly rotate the lens around a vertical axis until the ray fails to escape from the flat side of the lens.

5) Trace the new position of the flat side of the Plano-convex lens.

Calculations:

1) By measuring with a protractor show that the angle of incidence equals the angle of reflection for the plane mirror. Calculate the percent difference between the angles.

2) Find the focal point of the convex mirror by continuing the reflected rays back behind the mirror (use dotted lines). Measure the distance from the focal point to the mirror, then find the center of curvature. (Since we use spherical mirrors and lenses, the center of curvature is the center of the circle that contains the curve of the lens/mirror). Remember **2f = R**. All your answers must be in centimeters.

3) Find the radius of curvature and the diameter for the concave mirror. All your answers must be in centimeters.

4) On a separate piece of paper trace one side of the convex lens. Draw several lines tangent to the lens. Draw a perpendicular line from the tangent point back toward the center of curvature. Measure the distance from the tangent point to where your perpendiculars cross; this is R. Use R and the focal length of the convex lens (f is the distance from the convex lens to where the rays cross) in the lensmakers' equation:

$$\frac{1}{f} = (n-1)\left(\frac{1}{R_i} + \frac{1}{R_r}\right)$$

to find its index of refraction. Remember, you need the radius of curvature for *both* sides of the lens, which should be the same ($R_i = R_r$). For safety you should repeat this step with the other side of the lens. The value of the index of refraction should be around 1.5 ± 10%.

5) Using the diagram for the diverging lens above find the focal point of the concave lens. All your answers must be in centimeters.

6) For the Plano-convex lens, draw a line perpendicular to the new flat trace you drew where it intersects the optic axis. With a protractor find the critical angle.