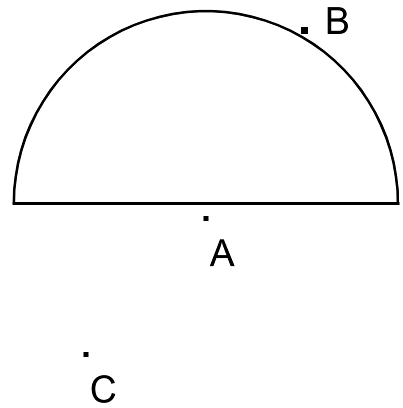
1. You may have noticed already that light rays *bend* whenever they cross a boundary from one transparent medium (such as air) into another, such as water. This bending is called "**refraction**". A convenient way to investigate the refraction of light is to stick pins into a piece of cardboard as in the illustrations at the right. Either the rectangle method *or* the semicircle method can be used.



 a. Place a clean sheet of paper on top of a sheet of carboard on a table top. Place the glass block or semicircle near the middle of the paper and trace its outline with a pencil.
 b. Place pin "A" at the center of the flat side of the glass semicircle or somewhere on the side of a transparent block, as in the illustration. Then place pin B somewhere near the middle of the curved side of the semicircle, or somewhere on the other side of the block, as in the illustration. Both pins should be perpendicular to the cardboard and should be in contact with the glass.
 c. Put your eye at a location such as "C" and look through the glass past pin A to pin B. Find a location for pin C so that it is several centimeters from A and so that the three pins appear to be aligned when you look through the glass. Line BAC then describes the path of a light ray which goes through the glass, grazing all three pins. After double-checking the pin alignment, mark the locations of the three pins so that the angles can be measured later.

2. The purpose of this experiment is to discover a law which describes the refraction of light. This law will be in the form of an equation relating two variable angles. Which angles will it involve?

3. Trace the paths of several different light rays crossing the air-glass boundary at point A. Cover the widest possible range of angles. Do whatever you can to minimize experimental error when making these measurements, and estimate their SDC's. *Make a graph while the experiment is in progress to see if a clear pattern exists.*

4. Find out if the light paths are reversible.
(See if light rays can cross the boundary in the opposite direction along the same path.)

5. A "normal line" is a line perpendicular to the boundary.
 a. If a ray arrives at a boundary by travelling along a normal line, does it bend when crossing the boundary? ___
 b. If a ray arrives at a boundary by travelling along a *diagonal* path (not along a normal line) then it __________ crosses the normal line while crossing the boundary. (always, sometimes, never)
 c. Suppose the boundary line is a circular arc: How can the normal line be constructed accurately? (Name the two points which will determine the normal line. One of them is the point where the ray crosses the boundary.) Please illustrate your answers to 5b & 5c. Label your diagrams clearly.

6. What law did you discover earlier that describes the refraction of *waves*? -Can you find any similarity between the refraction of waves and the refraction of light? -Is it possible to describe both kinds of refraction with the same equation? Clue: Be careful not to confuse the angle between the *ray* and the boundary with the angle between the *wave* and the boundary. Use a diagram to see how those angles are related.

1. Here are two questions about a light ray crossing a boundary between glass and air. One of the questions is ambiguous, the other is meaningful. It is useless to answer the ambiguous one, but you should answer the clear one and keep a copy of that answer for future reference. Also explain what is wrong with the question that is not written well.
   a. Let "i" represent the angle of incidence, measured between the incident ray and the normal. Let "r" represent the angle of refraction. Which of the angles is always the greater? _____
   b. Let "a" represent the angle between the the normal and the light ray in the air, and let "g" represent the angle between the normal and the light ray in the glass. Which angle is always the greater one? ____

* 2. Find out what is meant by a "refractive index". (Try a book.) Write the definition on the back of this paper and then use your experimental data to determine the refractive index of the transparent material that your block was made from. Remember to show how the uncertainty of this result is calculated.

* 3. Some students feel that the refraction experiment on page 151 tests the hypothesis that light is a kind of wave motion. Others say that it does not test that idea at all. State and explain your opinion.

4. Draw a glass semicircle like the ones used in the optical refraction experiment on page 151. Let its diameter be ten centimeters. (Make this an accurate, full-scale drawing. Use a compass and ruler.)
   a. Draw several rays of light entering the flat side. Make them all perpendicular to the flat side, and space them one centimeter apart.
   b. Review the law that enables you to predict how much refraction occurs when a ray crosses a boundary. Use that law to predict how much each ray will bend when it crosses each boundary if the refractive index of the glass is 1.5.
   d. Make an accurate drawing showing the rays emerging from the glass.
   e. Extend those rays at least 20 centimeters beyond the glass.

5. A "plano-convex lens" is a solid piece of glass with one flat side and one bulging (convex) side. The "axis" of the lens is a line through the center of the lens, perpendicular to the flat side. (The axis will pass through the ____ of curvature of the _____ side.) Let "R" represent the convex side's radius of curvature. Let "n" represent the refractive index of the glass. Let the thickness of the lens be much less than R, so that the diameter of the lens is also small compared to R.
   a. Use a compass and ruler to draw such a lens in cross-section.
   Draw the axis and mark the center of curvature clearly.
   b. Draw the path of one light ray parallel to the axis, entering the flat side.
   This is similar to #4, but the glass is much thinner.
   c. Let "h" represent the distance between that ray and the axis:
   If you followed the instructions you can see that h is much _______ than R. (greater or less?)
   d. Construct a line normal to the convex surface at the point where the ray emerges from the glass.
   e. In #1 we decided to use the letter "__" to represent the angle between this normal and the part of the ray that is in the glass. Write a trigonometric equation relating that angle to h and R.
   f. Draw the ray as it emerges from the glass. You needn't use a protractor, but be sure to use #1.
   g. What letter usually represents the acute angle between the normal and the emerging ray? ____
   h. Use what you have learned about refraction to write a trigonometric equation relating that angle to n, h, and R: _____ = _____

6. Use simple trig to create a formula for the distance between the thin lens in #5 and the place where the emerging ray crosses the axis. (This task is especially simple if you recall that the sine or tangent measure of a small angle is almost exactly the same as the _____ measure of that angle.)
   a. How does that distance depend on "h"?
   b. Why is that distance called the "focal length" of the lens?

7. Does #6 explain how a magnifying glass can be used to start a fire on a sunny day? Unlike the lens in #6, magnifying glasses are usuall convex on both sides. Is there any significant difference between the behavior of a double-convex lens and the behavior of a plano-convex lens?

8. Draw two diagrams showing how a magnifying glass can be used to start a fire. Let the sun's rays be parallel to the axis of the lens in the first diagram. Let the lens be tilted slightly in the second diagram so that the sun's rays are not parallel to the axis as they enter the lens.

1. Draw a large circle representing a solid sphere of transparent material. Draw a straight line representing a light ray going toward some point on the sphere, but not toward the center.
2. Draw another straight line segment inside the sphere to show how the light ray is "refracted" (bent) when it enters the sphere.
3. Draw a dotted "normal line" from the center (point "O") through the ray's entry point. Let "θ" represent the acute angle between the original ray (in air) and the normal line. Let "ϕ" represent the angle between the refracted ray (inside the sphere) and the normal line. Use those letters to label the angles in your diagram.
4. Make another dotted normal line through the point where the ray emerges from the sphere. What do we know about the angle between that normal line and the ray inside the sphere?
5. Whenever a light ray crosses a boundary between two different transparent materials it is partially reflected. (That's how sunlight reflects off windows.) Therefore some of the light will be "internally reflected" at the boundary where you drew the second normal line. (We'll call that point "R".) Draw another straight line segment inside the sphere to describe that internally reflected ray.
6. What do we know about the angle between the reflected ray and the second normal line?
7. Draw a third normal line through the point on the sphere's surface where the reflected ray emerges from the sphere. (We'll call that point "E".) What do we know about the angle between the reflected ray and the third normal line?
8. When the light ray emerges from the sphere at point E it must be refracted once again. Show that bending clearly in your diagram. What do we know about the acute angle between the emerging ray and the normal through point E?
9. If drawn correctly, the original incoming ray in #1 and the emerging ray in #8 will not be parallel. If you extend them they must intersect somewhere on the _______ line through point __. *The diagram must be symmetrical about that line.* Let's label that intersection point with the letter "A".
10. Copy triangle ORE. We have already decided that angles ORE and REO are equal to ____. Therefore angle ROE must be equal to _________, by the interior angles theorem.
11. Copy triangle EOA. The "vertical angles" theorem tells us that angle OEA must equal ___. We established in #10 that angle AOE equals _________. Therefore the unknown angle ("α") in that triangle can be determined with the interior angles theorem: α = _____________
12. Use Snell's law to eliminate ϕ from eq. 11: α = _____________
13. Imagine an evenly-spaced a set of parallel rays entering the sphere:
    a. Each ray has its own entry point and its own "θ" value. The smallest is ____, and the biggest is ___.
    b. Each emerging internally reflected ray has its own "α" value, telling us which way it goes after it comes out. Equation 11 tells us how α depends on θ. Use a computer or graphing calculator with the clue in 13a to find out what the graph of that relation looks like.
    (For glass the refractive index is between 1.5 and 1.6. For water it is 1.33.)
14. Can you find a region on that graph where changes in the value of θ cause practically no change in α? If so, let "α_S" represent the special "α" value where that occurs. (Indicate it on your graph.) Will the emerging set of internally reflected rays be evenly distributed over all possible "α" values?
15. Imagine standing in an open field as the sun sets in the west. East of you there are many spherical water droplets falling through the air. Sunlight reflects from the droplets in the manner described above. <u>Some</u> of them are positioned so the rays emerging at the preferred angle will go toward you. *Please illustrate*. You will see them as bright sources of light. What pattern will they form, from your viewpoint? -How is your answer affected by the fact that refractive index depends slightly on color?