Experiment 21: Geometric Optics

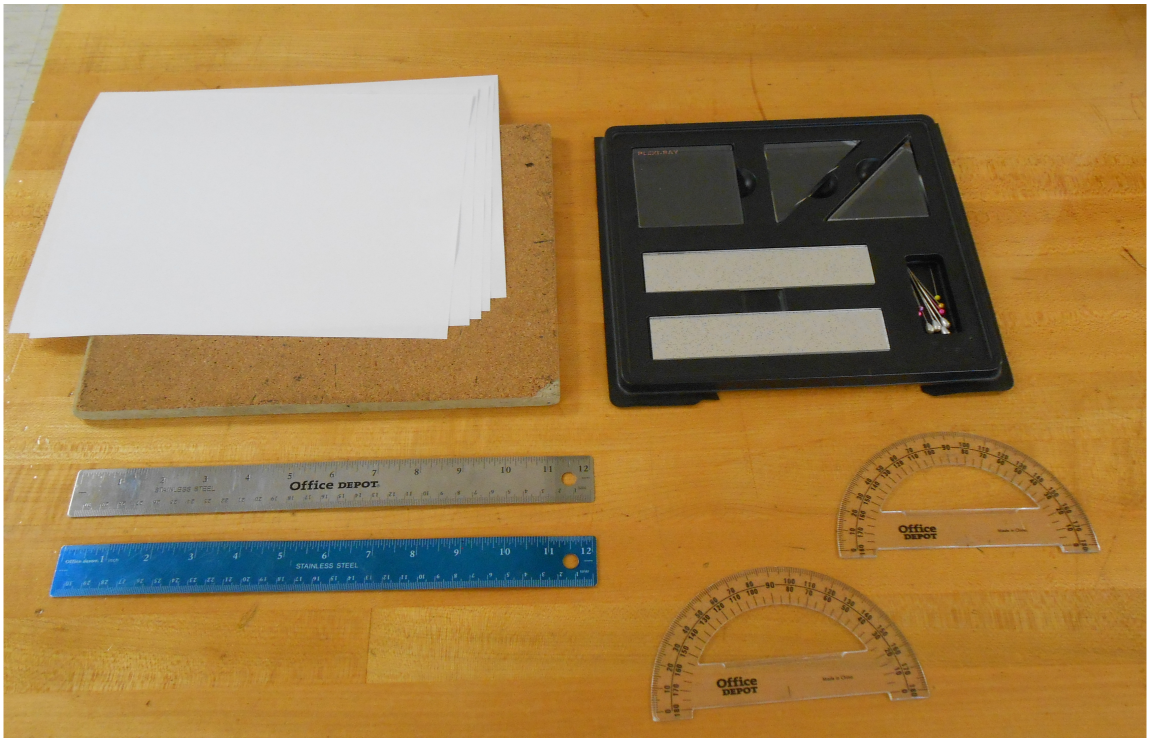

Figure 21.1: Geometric Optics Equipment

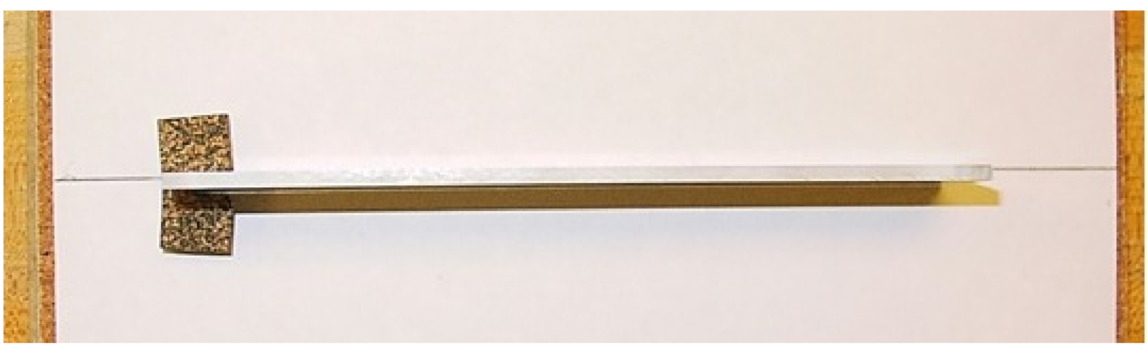

Figure 21.2: Mirror Placement: The “Plexi-Ray Kit” contains a small piece of cork or plastic to stabilize the mirror during your experiment. The mirror must sit on the paper, not on the stabilizer.

EQUIPMENT

Plexi-Ray Kit
Corkboard
Paper (9 sheets per 2-member team)
(2) Protractors
(2) 30-cm Rulers
(2) White Pins
(2) Color Pins
Lens Cleaning Towelettes (TA’s Table) - optical elements may need to be cleaned

Advance Reading

Text: Geometric optics, law of reflection, law of refraction, index of refraction, total internal reflection, critical angle, parallax, real image, virtual image, speed of light.

Objective

The objective of this experiment is to study the behavior of light using the ray model.

Theory

We will investigate light reflecting from objects as well as light that is transmitted through objects.

An image viewed in mirror is a *virtual image* as are images for some lenses. Light rays do not actually pass through a virtual image. A virtual image cannot be projected on a screen. The image seen in a mirror does not appear to be at the surface of the mirror, but rather to be located some distance behind the surface. The image appears to be located the same distance behind a plane (flat) mirror as the object is in front of the mirror. We investigate virtual images for plane mirrors in *Part 1* and *Part 2* of this experiment; we will investigate virtual images from a lens in *Experiment 22*.

The **Law of Reflection** states that when light reflects from a smooth, flat surface (*e.g.*, a plane mirror), the angle of incidence equals the angle of reflection:

$$\theta_i = \theta_r \tag{21.1}$$

In geometric optics, all angles are measured with respect to the normal (the perpendicular). We investigate this law in *Part 3* of this experiment.

When light passes from a vacuum into a transparent medium, it slows down. The ratio of the speed of light in a vacuum, c, to the speed of light through a transparent medium, v, is the **index of refraction**, n, of that medium. $n \geq 1$ at all times, since:

$$n = \frac{c}{v} \tag{21.2}$$

The speed of light in a vacuum, c, has been defined: 299,792,458 m/s, or approximately 3×10^8 m/s. Note that each material has its own index of refraction; n is a property of the medium.

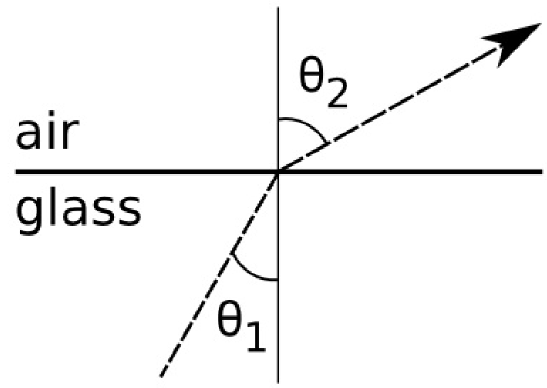

Figure 21.3: Refraction

The **Law of Refraction (Snell's Law)** describes the behavior of a ray of light that passes from one medium into another:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \tag{21.3}$$

where n_1 and n_2 are the indices of refraction for the two media, θ_1 is the angle of incidence, and θ_2 is the angle of refraction. We investigate the law of refraction in *Part 4* of this experiment.

Total Internal Reflection is a special case in which light is unable to cross the boundary between the two media. Consider Eq. 21.3 and a specific combination of media, such as glass and air, with light passing through a medium of higher n (n_1) into a medium of lower n (n_2). As θ_1 increases, θ_2 increases more rapidly. θ_1 can reach a value that results in θ_2 being equal to 90°. When this happens, the light will not exit the medium. It will be totally internally reflected. This θ_1 angle is called the *critical angle*, θ_C:

$$\theta_1 = \theta_C \quad \text{when} \quad \theta_2 = 90^\circ \tag{21.4}$$

Note that each combination or media can have a different θ_C. Note also that total internal reflection only happens when light passes from a medium of higher index of refraction into a medium of lower index of refraction. Total internal reflection is a part of our everyday world - fiber optics, for example, used for cable TV. We investigate total internal reflection in *Part 5* of this experiment.

Parallax is *the effect whereby the position or direction of an object appears to differ when viewed from different positions*. This means that the object and the two observations points are not collinear. Fig. 21.4 and Fig. 21.5 represent the effect.

The apparent change in direction can be useful for determining the distance from Earth to a star. The diagram below is, of course, not to scale.

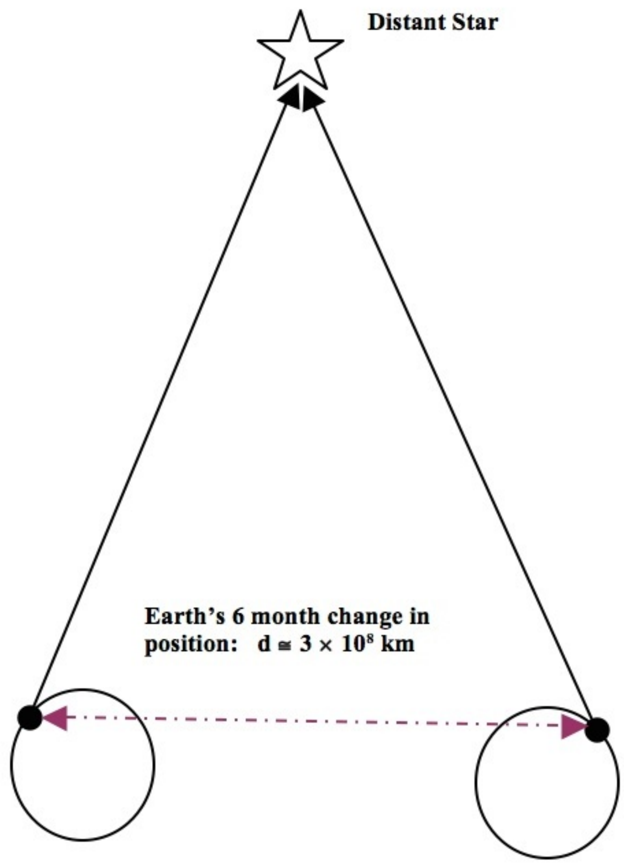

Figure 21.4: Parallax - One Object

Parallax is larger when the object is closer. While parallax can present problems when making measurements, it is very useful for determining the position of a virtual image.

Consider two objects that are aligned from your initial position (they appear to be one object). When you change your position, each object will appear to be displaced but by a different amount. The objects appear to separate (Fig. 21.5). They are no longer aligned with your position.

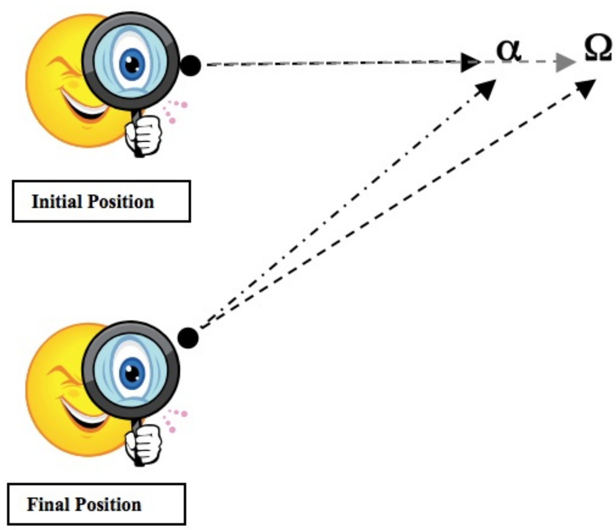

Figure 21.5: Parallax - Two Objects

We make use of parallax (2 objects) in *Part 1* and, if you so choose, *Part 2* of this experiment.

Since a virtual image cannot be projected on a screen, it can be difficult to determine its location. Consider an object whose image is observed in a mirror. The image is a virtual image. To determine the position of a virtual object, one can align a real object (pin) with a virtual object (image of a different pin). If the observer changes their position and the two objects do not separate, the real and virtual objects are in the same location.

Name: ____

1. State the law of reflection. Write the equation. (10 pts)

2. State the law of refraction. Write the equation. (10 pts)

3. What is the definition of a virtual image? (10 pts)

4. What is total internal reflection? (10 pts)

5. Define *critical angle*. (10 pts)

6. Define *parallax*. (10 pts)

7. Write Snell's Law. Using Eq. 21.4, derive the equation for the critical angle: $\theta_C =$ ________. (40 pts)

PROCEDURE

1. Read through *Step 6* before beginning. All arrangements (paper) should be aligned with the edge of the table.

2. Measure all normal lines with a protractor to ensure they are 90°; do not estimate. Draw the lines long enough to allow accurate measurements using the protractor. Do not fold the paper!

3. When placing more than one pin, separate them as much as possible (*e.g.*, one pin close to the mirror, the other pin close to the edge of the paper). This will increase accuracy and improve your results. When aligning objects and images, close one eye.

PART 1: Parallax

4. For *Part 1*, you will use a *virtual image* (the mirror image of a pin); use the image of the white pin as the first object and *a real object* (a color pin) as a second object. If the second object is placed at a location other than the location of the first object, note that when you change your position there is a shift in the apparent position of the two objects. You will see two images (Fig. 21.5); they will not be aligned.

5. When parallax occurs, there are two possibilities:

   - The pin is in front of the virtual image. Parallax is larger for the pin.
   - The pin is behind the virtual image. Parallax is smaller for the pin.

6. If the pin is placed at the same location as the virtual image and you change your position, there will be no change in the apparent position of the two objects (*i.e.*, there will be no separation of the objects). You will see only one image, thus eliminating parallax.

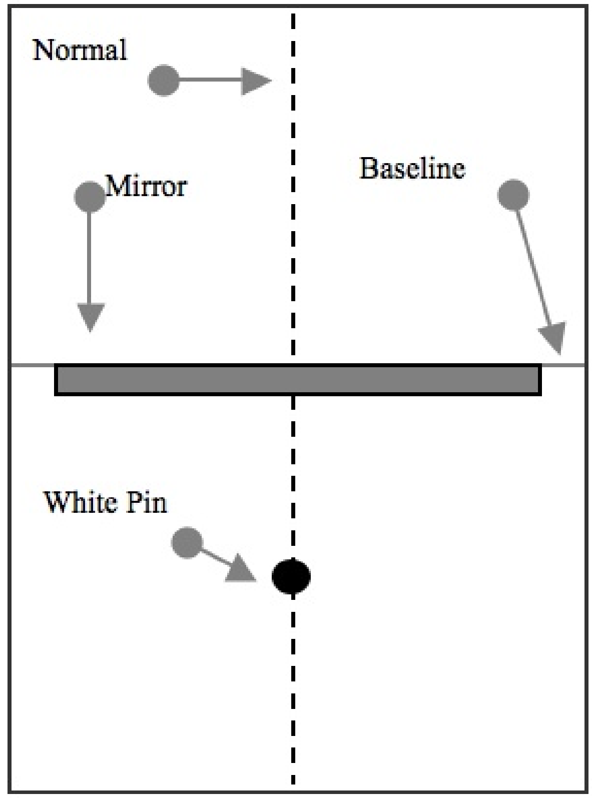

Figure 21.6: Parallax

7. Refer to Fig. 21.6. Draw a line across the center of a sheet of paper (baseline) and a line normal to the baseline down the center of the paper.

8. Place the paper on the corkboard and place the back of the mirror on the baseline (Fig. 21.2). Place a white pin midway on the normal in front of the mirror. The image of this pin will be *object 1.*

9. Place a color pin on the normal behind the mirror. This pin will be *object 2.*

10. Observe from an orientation to the right or left of the normal. If *object 1* and *object 2* are not aligned, move *object 2* towards or away from you, along the normal, until they are aligned. (Your partner will help you stay on the normal.)

11. Measure and record the distance from the mirror to the white pin, d_0, and the distance from the mirror to the second pin, d_i.

PART 2: Image from a Mirror

12. Team performs once; take turns for each vertex.

13. Refer to Fig. 21.7. Draw a baseline across the center of a sheet of paper. Place the triangular plexiglass in the center of the front half of the paper, trace around it, then return it to the kit. Label the vertices of the triangle A, B, and C. Place the paper on the corkboard and the mirror on the baseline.

14. You may use either the parallax method or the following method to determine the position and dimensions of the virtual image of the triangle.

15. Consider Fig. 21.7. Two points are required to designate a particular line (*e.g.*, two a' or two a''). (Always separate the pins as much as possible to improve your results.) Two intersecting lines designate a particular point (*e.g.*, A').

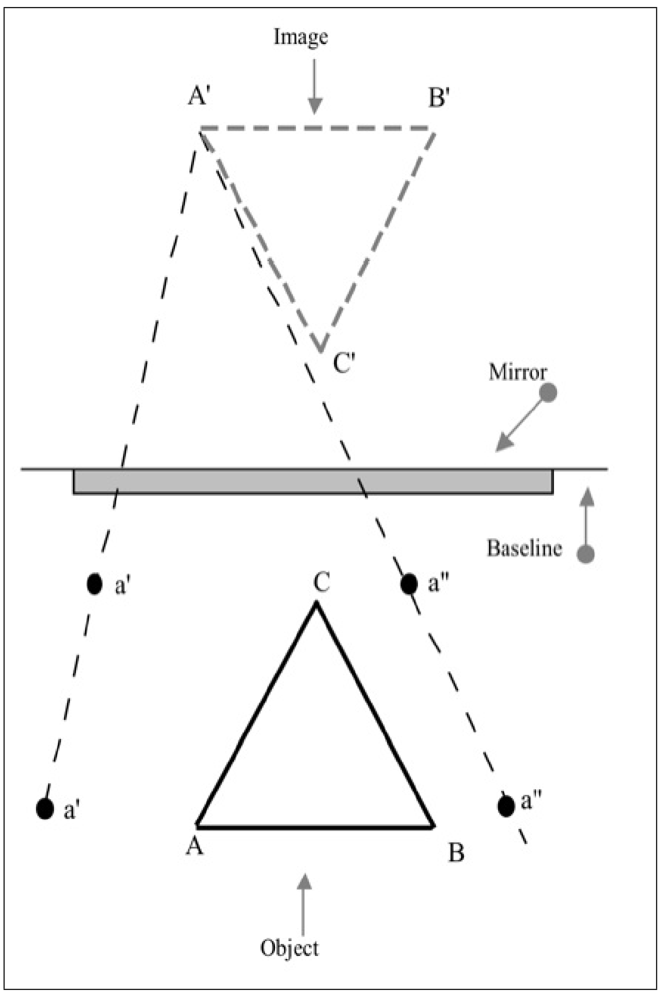

Figure 21.7: Image from a Mirror

16. Place a white pin at vertex A; the image of the white pin is the *object*. Observe from the left and align two color pins (sighting pins) with the object.

17. Mark the positions, then remove the pins and label the positions of the sighting pins a'.

18. Repeat, observing from the right. Mark the sighting pin positions as a''.

19. Repeat for vertices B and C (obtaining two sight lines for each vertex).

20. Draw a line through the two a' points, the length of the paper. Repeat for each pair of points. Mark the intersection of the a' and a'' lines as A'. Repeat for B' and C'.

21. Connect the points A', B', and C'. Measure and compare the dimensions of the object and image triangle.

PART 3: Reflection

22. Refer to Fig. 21.8. Draw a baseline across a sheet of paper, near the top. Draw a line normal to the baseline down the center of the paper. Draw a line to the left of the normal (incident line) with angle θ_i between 25° and 35°.

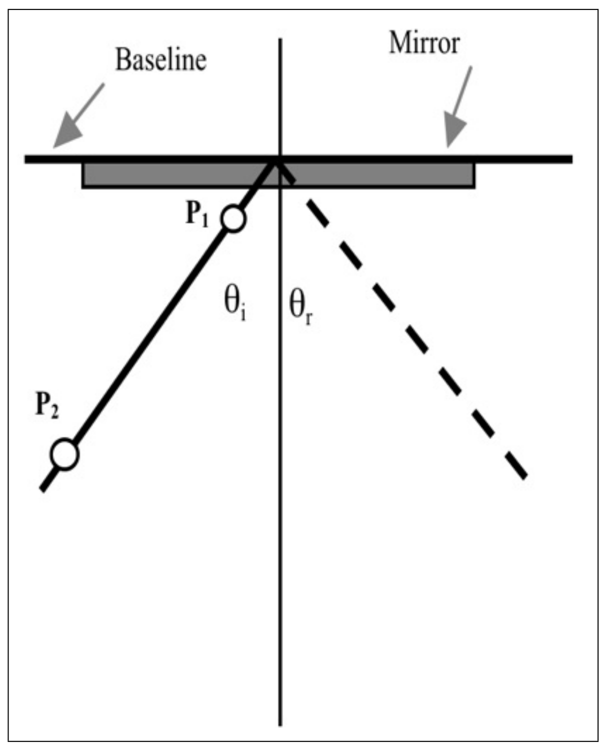

Figure 21.8: Reflection

23. Place the two white pins on the incident line. Label these positions P_1 and P_2.

24. Look at the mirror from the right side of the normal so that you can see the image of the first two pins. Adjust your position so that the *images* of the white pins are aligned; align two color pins with them.

25. Label these two points P_3 and P_4.

26. Draw a line connecting point P_3 and P_4 to the baseline. Measure and record θ_i and θ_r.

PART 4: Refraction

27. Place the plexiglass square at the center of a sheet of paper and trace around it.

28. In the upper-left corner of the traced square, draw a line normal to the square, about 2 cm from the corner (Fig. 21.9).

29. Draw an incident line (θ between 25° and 35°). Place the paper on the corkboard, the square on its traced outline, and two white pins on the incident line. Label their positions P_1 and P_2.

30. Look *through* the plexiglass square from the edge opposite the pins and close your left eye. (It will help if your partner holds a piece of paper behind the square to block images of other objects in the room.)

31. Adjust your position until the two white pins are aligned, then place two sighting pins (color pins) that align with the image of the two white pins. Label these points P_3 and P_4.

32. Draw a line connecting P_3 and P_4 to the edge of the square. Draw a line normal to the square through this intersection (refer to Fig. 21.10).

33. Draw a line inside the square to connect the normals (Fig. 21.10).

34. Measure and record each θ. You have 2 sets of data, A and A' (top and bottom).

35. Consider the law of refraction and Fig. 21.10.

    - *Situation A*: As light enters the plexiglass from the air, it bends towards the normal, since it enters a medium with an index of refraction greater than the index of refraction of the medium it is leaving.
    - *Situation B*: As light enters the air from the plexiglass, it bends away from the normal, since it enters a medium with an index of refraction lower than the index of refraction of the medium it is leaving.

36. Therefore, $\theta_1 = \theta'_2$ and $\theta_2 = \theta'_1$. ($n_{air} = 1.0003$)

37. Calculate the index of refraction of the plexiglass for each situation (situation A and A').

38. Average your values of $n_{plexiglass}$ and calculate the speed of light through the plexiglass.

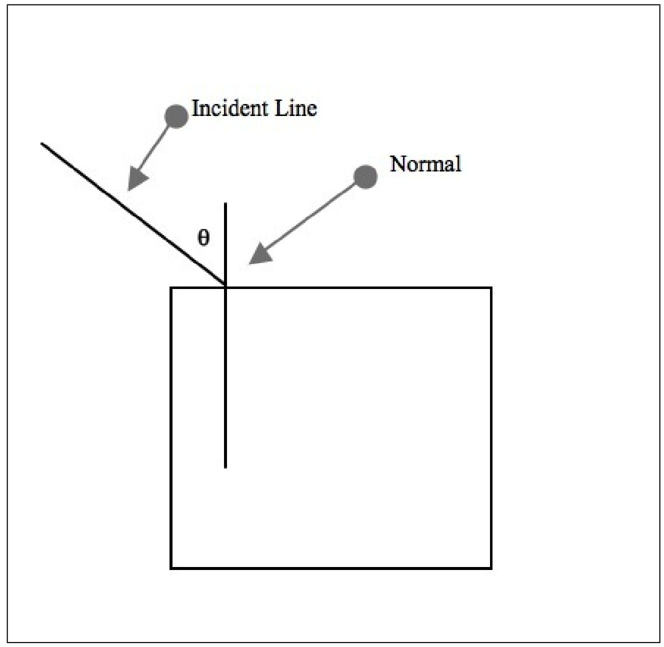

Figure 21.9: Refraction - Initial

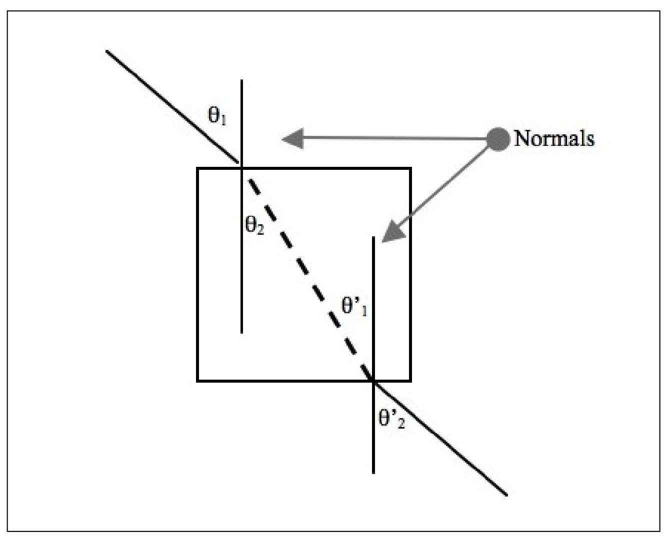

Figure 21.10: Refraction - Final

PART 5: Total Internal Reflection

39. Place the plexiglass triangle in the center of a sheet of paper and trace around it. Draw a line normal to the bottom edge (the long side), about 1 cm from the left corner (Fig. 21.11). Place the paper and triangle on the corkboard; place two white pins on the normal line with their positions labeled P_1 and P_2.

40. Look *through* the right side of the bottom edge of the triangle and adjust your position until the two white pins are aligned. (It will help if your partner holds a piece of paper behind the triangle to block images of other objects in the room.) Now align two color pins with the white pins *as viewed through the plexiglass*. Label these position P_3 and P_4.

41. Return the triangle and pins to the kit; place the paper on the table.

42. Draw the path of the light ray by:
    - Extending the normal ($\overline{P_1P_2}$) to the far edge of the triangle
    - Connecting P_3 and P_4, extending the line to the far edge of the triangle
    - Connecting the line segments ($\overline{P_1P_2}$ to $\overline{P_3P_4}$) at the top (far edges of the triangle)

43. Draw a line normal to the edge of the triangle where each light ray ($\overline{P_1P_2}$ and $\overline{P_3P_4}$) intersects the far edge of the triangle.

44. Measure θ_1 and θ_2 at each location where the light reflects internally. You have two sets of data, A and A' (right and left).

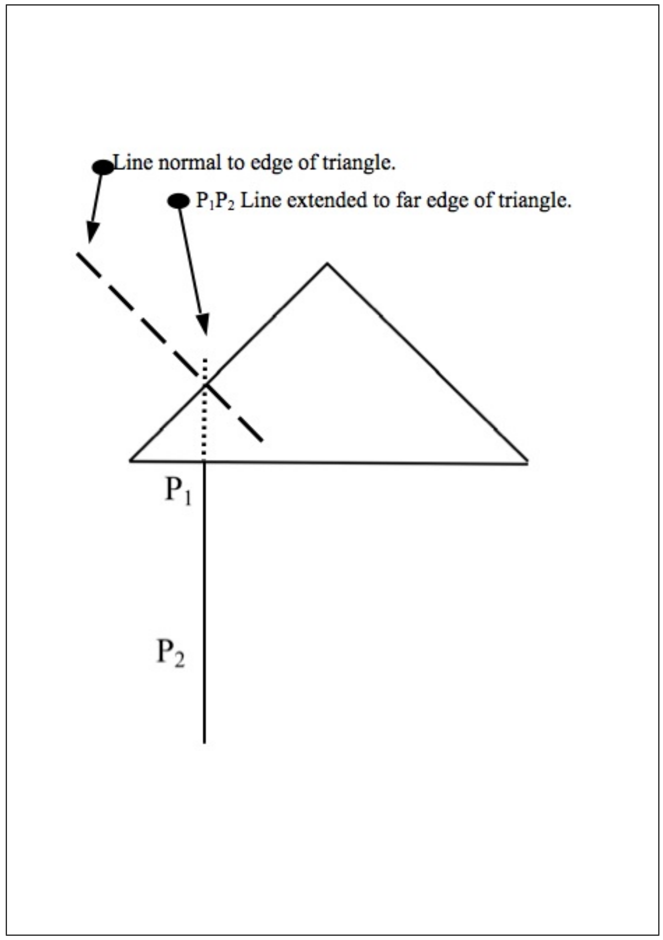

Figure 21.11: Total Internal Reflection

QUESTIONS

1. Calculate θ_C for plexiglass in air (using your average value of "n" from *Part 4*).

2. What is the shortest height a plane mirror must be so that a person who is 1.6 meters tall is able to see his or her whole body? Draw a ray diagram to support your answer.