CENCO Physics Selective Experiments In Physics

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REFRACTION OF LIGHT BY LIQUIDS
(Refraction Tank)

OBJECT: To observe the change in direction of a ray of light as it passes obliquely through the glass/liquid inter-face of a tank containing a transparent liquid and, by observing the direction of the light inside and outside the tank, to calculate the index of refraction of the liquid.

METHOD: A tank that has parallel, glass, side walls contains a transparent liquid whose index of refraction is to be determined. Light from a narrow vertical slit hanging on one of the walls changes direction as it passes obliquely through the water/glass interface at the opposite wall. The initial and final directions are observed for various angles of incidence and, by substituting into Snell's Law the data from each pair of observations, the index of refraction of the liquid is calculated. This procedure is conducted for several liquids.

THEORY: When thrust into a pond of water, a stick appears to an observer on the shore to be bent at the surface of the water. Also, the pond appears to be less deep than it actually is. These illusions, observed for thousands of years, are due to the fact that light changes direction as it passes obliquely from water into air or, for that matter, from air into water. More generally, light changes direction when traveling obliquely between the interfaces of any pair of transparent materials in which the speed of light is different.

Consider Fig. 1 in which a ray of light is shown to change direction as it travels from one transparent medium into another. Angles θ_1 and θ_2 are the angles the ray makes with the normal to the interface in the respective media. Angle θ_1 is called the angle of incidence, and angle θ_2 is called the angle of refraction. It should be noted that a ray traveling in the opposite direction will follow the same path.

For a given wavelength of light and for a given pair of transparent materials, it was empirically discovered that the ratio of sin θ_1 to sin θ_2 is a constant. That is, the ratio has the same value regardless of the angle of incidence. This ratio, called the *relative index of refraction*, is conventionally assigned the symbol n_{21}:

$$n_{21} = \frac{\sin\theta_1}{\sin\theta_2} \tag{1}$$

This relationship is known as Snell's law in honor of Willibrord Snell (1591-1626).

If the first medium is a vacuum, the value of the ratio sin θ_1/sin θ_2 is called *the absolute index of refraction* of the second medium-or, simply, its index of refraction, and it is assigned the symbol *n*, either with or without an identifying subscript. For practical purposes, the first medium can be air instead of a vacuum, for the difference in the resulting ratios is only about 3 parts in 10,000.

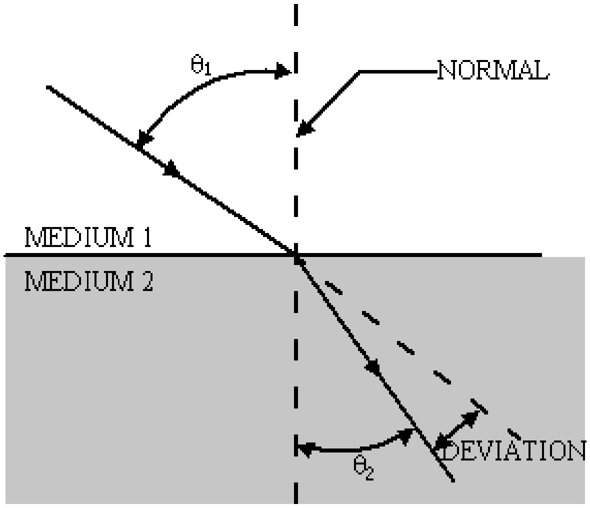


Fig. 1. A ray of light changes direction, i.e. deviates, when it passes obliquely through the interface of two different transparent materials.

The fact that sin θ_1/sin θ_2 is a constant when light travels from one transparent medium into another follows from the wave theory of light. Consider Fig. 2: abroad beam of light falls on the plane surface between two transparent materials which differ in the sense that light travels more slowly in the second material than in the first. Line *OP* is drawn perpendicular to the direction of travel in the first medium ; thus it represents the intersection of a wavefront with the plane of the figure. (A *wavefront* is a surface all points of which are in the same phase of vibration.) According to Huygens' assumption, each point on a wave front is the source of new waves, and the envelope of these from all points gives anew wavefront an instant later. Since the speed of light is slower in the second medium than in the first, by the time the disturbance from *P* reaches the surface at point *Q* the disturbance from *O* will have traveled the lesser distance *OR* into the second medium. The new wavefront at that instant can then be represented by the line *RQ*, and, since the wavefront and its direction of travel are mutually perpendicular, the beam will have changed direction. It will have been refracted toward the normal: angle θ_2 is less than θ_1. Note that *OQ* is the common hypotenuse of the triangles *OQP* and *OQR* and that the angles *POQ* and *ROQ* are equal to θ_1 and θ_2 respectively. Thus

$$\sin\theta_1 = PQ/OQ$$

and

$$\sin\theta_2 = OR/OQ$$

By eliminating OQ between these equations we get

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{PQ}{OR}$$

Now, since *PQ* and *OR* are distances traveled in the same time, their ratio is equal to the ratio of the speed of light in the two media. Therefore

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2} \tag{2}$$

where v_1 is the velocity of light in the first medium and v_2 is the velocity in the second. This ratio is, of course, a constant, in agreement with Snell's law.

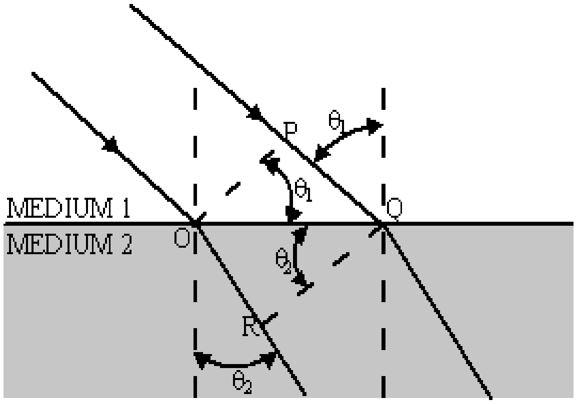


Fig. 2. Construction to show the wave theory explanation of refraction. The wave-front RQ in the second medium is not parallel to the incident wave-front OP if the speed of light is not the same in the two media. The direction of travel of the beam is therefore changed.

It can now be shown that the index of refraction of a material depends on the velocity of light in that material. For, if the first medium in Fig. 2 is vacuum (or air), the ratio, by definition, is the index of refraction of the second medium. Hence, by Eq. (2), its index of refraction *n* is given by the ratio

$$n = \frac{c}{v} \tag{3}$$

where v is the velocity of light in the material and c is the velocity of light in empty space. (c = 3.00 x 10^8m/sec, given to three significant figures.)

Finally, the value of the constant ratio between the sine of the angle of incidence and the sine of the angle of refraction for any pair of transparent materials turns out to be equal to the inverse ratio of the individual indices of refraction. For, by Eq. (3), the individual indices have the values $n_1 = C/V_1$ and $n_2 = C/V_2$, where v_1 and v_2 are the velocities of light in the respective media. By eliminating *c* between these two equations we get

$$\frac{n_1}{n_2} = \frac{v_2}{v_1} \tag{4}$$

From a comparison of this equation with Eq. (2) it is apparent that

$$\sin\theta_1/\sin\theta_2 = n_2/n_1 \tag{5}$$

This equation can alternatively be written

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \tag{6}$$

Dispersion. When a narrow beam of white light passes obliquely into any transparent medium, the beam spreads out slightly and colors can be observed. This phenomenon is called *dispersion*. It is due to the fact that the different colors that comprise visible light travel at different speeds in the material. The blue (short wavelength) radiation at one end of the spectrum has a slightly lower speed in almost all substances than radiation at the red end. Hence, blue is deviated more than red. In Fig. 3, dispersion by a prism is shown with some exaggeration for clarity purposes, since the difference in speed of the two colors is relatively small in most substances.

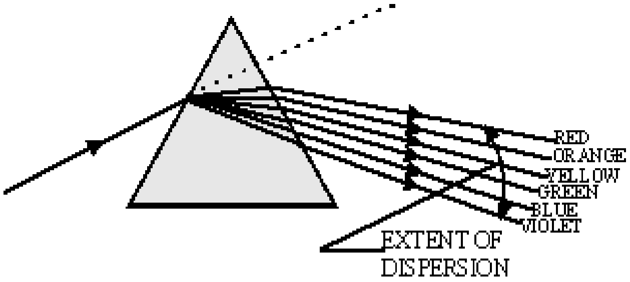


Fig. 3. Illustrating dispersion by a prism. When a ray of light passes obliquely into any transparent medium, the various component colors (wavelengths) in the radiation are deviated by different extents and the light is spread out into a fan-shaped beam. As the light emerges from the medium, a further dispersion occurs. for most transparent materials, the greater the deviation, the greater the dispersion.

Dispersion can be observed qualitatively only with the apparatus designed for this experiment. To make a satisfactory measurement of the variation of index of refraction with wavelength it is necessary to use another instrument, such as a spectrometer, together with a hollow prism containing the liquid. As light emerges from the prism, at the second interface, a further dispersion occurs.

APPARATUS: The refraction apparatus shown in Fig. 4; water, alcohol, benzene or other liquids whose index of refraction is to be determined. The refraction apparatus consists of a metal tank with two parallel glass side walls and a pair of metal slits. The tank is mounted in one corner of a square, flat metal base. A swinging index arm extends from the bottom of the tank to the opposite corner of the

base. A cross-sectional ruling and a protractor are lithographed on the base to permit measurement of the angular position of the arm.
Additional optional apparatus: low-voltage lamp that has a small filament; matching socket and matching transformer.

PROCEDURE: Place the refraction apparatus on a horizontal surface that is at such a height as to permit convenient sighting through the tank for making the observations described below. The apparatus should be oriented with the tank at the rear of the base so that the index arm and the protractor are immediately adjacent to the observer. Loosen the thumb screws that secure the tank to its base and adjust the position of the tank until the vertical line etched on the front plate of glass is directly above the screw that holds the index arm and the plane of the glass is perpendicular to the zero line of the protractor. Secure the tank in this position by tightening the thumbscrews.

Fig. 4. The Refraction Apparatus. When the tank is partially filled with a transparent liquid, one can see the slit that hangs on the back plate of glass by sighting either through the liquid or above it. By using the index arm, one can measure the angle of refraction and the corresponding angle of incidence of light traveling from water into air.

Part I. *Qualitative Observation of Refraction*. It is instructive to observe visually the refraction that occurs when a ray of light passes obliquely from one transparent medium into another. However, to do so with the apparatus designed for this experiment one must have available a bright concentrated source of light; if such is not available this part of the experiment may be omitted. A low-voltage lamp that has a small filament, such as a flashlight bulb, is suitable. If the lamp is operated by a transformer that delivers a voltage slightly higher than the rated voltage of the lamp, the resulting beam of light will be just that much brighter.
Half fill the refraction tank with water and hang one of the metal slits on the back glass plate. Mount the concentrated light source a short distance behind the slit and at a slightly higher level than the floor of the tank so that the path of the beam in the water is visible on the floor of the tank. The path of the beam emerging from the front side of the tank can be made visible on a piece of cardboard or stiff sheet of paper held next to the front plate and in the same plane as the floor of the tank-tilted slightly upwards if necessary. One can then see directly the change in direction of the beam of light as it passes from water into air. Make a rough sketch of what is observed for several angles of incidence.

Part II. *Quantitative Measurements of Index of Refraction*. Half fill the tank with water and hang one of the metal slits on the back glass plate. Place a well-lighted sheet of paper a short distance behind the slit. (Alternatively, the slit can be illuminated by the light source suggested for Part I.) It should then be possible, by sighting, to line up three things: the slit on the back plate, the vertical etched line on the front plate, and the cross line on the movable index arm. With the tank half filled with water, one can sight either through the water or above it. When one's line of sight is above the surface, the position of the index arm (as read on the protractor) gives the direction in which the light travels in the water. When the line of sight passes through the water, the reading of the protractor gives the direction of the light as it emerges from the tank. Since protractor readings are relative to the normal to the glass, the two readings give θ_2 and θ_1, respectively, for calculating n, the index of refraction of water, by using Eq. (1). If it is difficult to see the etched line on the front plate of glass, hang the second slit on the front plate so that it straddles the etched line.
Some preliminary experimenting is required in the making of alignments so that readings can be repeated satisfactorily. One method is to move the index arm to one side, line up the back slit and the etched line (with one eye, of course) , and then bring the cross line of the index arm into the same line of sight. To minimize personal bias, this should be repeated by starting with the index arm on the opposite side. To obtain a satisfactory average value for the direction of the light, take six separate sightings for each angle; that is, six for θ_1 and six for θ_2.
Obtain data for θ_1 and θ_2 at five different angles of incidence between about 10° and 40° in the water. Record the resulting average values of θ_1 and θ_2 in a separate table; in subsequent columns enter the values of sin θ_1, sin θ_2, and the calculated ratio $\sin\theta_1/\sin\theta_2$. The sine of an angle can, of course, be obtained from a trigonometry table. However, note that it can also be read directly from the cross-section ruling which, together with the protractor is etched on the base at the front of the tank. Finally, the average of the several values of the ratio $\sin\theta_1/\sin\theta_2$ should be compared with the accepted value of the index of refraction of water at room temperature.
In the same manner as described above, find the index of two other liquids, say alcohol and benzene. (Do not use a liquid that will chemically react with the aluminum or with the caulking compound used to seal the glass plates in the tank.)

Part III. *Qualitative Observation of Dispersion*. As stated above, dispersion can only be observed qualitatively with the refraction tank apparatus. Furthermore, the dispersive power of most liquids is small; therefore, in this part of the experiment, it is desirable to use a liquid such as benzene because its dispersive power is greater than that of water; Also, to observe dispersion with this apparatus it is necessary to use a bright, concentrated source of light. The low-voltage, small-filament lamp suggested for Part I is a suitable source. It is also necessary that the angle of incidence be large.
The metal slit on the back glass plate is placed at one end of the plate, and the concentrated source of light is mounted a

short distance behind the slit and at such a location that the ray of light inside the liquid makes the largest possible angle with the normal to the glass. Then, by moving your head slowly from side to side when sighting through the liquid, you can observe a slight change in the color of the light that reaches the eye. Sketch what is observed.

Were the colors observed due to dispersion that occurred as the light *entered* the tank or as it *left* the tank? Draw a ray diagram showing how a red ray and a blue ray (same angle of incidence) pass through the tank. The emerging rays must, of course, be parallel to the incident ray. Do the predictions of the diagram agree with what was observed?

PROBLEMS: 1. The speed of light in air is 3.00 x 10^8m/sec. Calculate the speed of light in glass that has an index of refraction of 1.5.

2. Given a thick plate of glass that has parallel sides and a refractive index of 1.5, let a ray of light fall on one side of the plate at an angle of incidence of 45° and emerge on the other side. Use Snell's law to compute the complete path of the ray, and draw an accurate diagram.

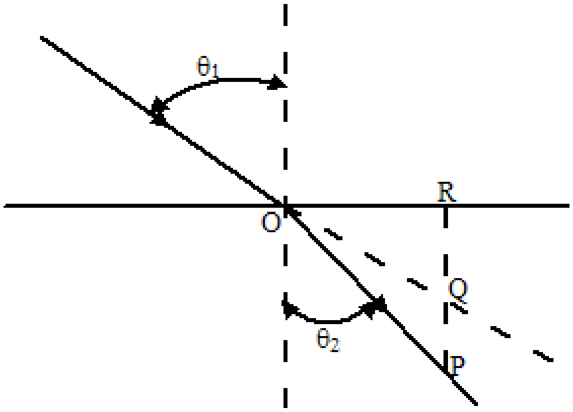
3. Prove that the ray which emerges from the glass plate in Problem 2 is parallel to the incident ray by (a) arguing on the basis of the geometry of your figure and (b) arguing on the basis of symmetry principles.

4. Several centuries before the discovery of Snell's law, Ptolemy stated in a book on Optics that when a ray of light passes between two transparent materials, if the angle of incidence is not too large, the ratio of the value of the angle of incidence to that of refraction is approximately a constant. In other words, the ratio θ_1/θ_2 has approximately the same value for all angles of incidence if the angle is small. Prove that this follows from Snell's law.

5. A ray of light passes obliquely through a thick glass plate that is immersed in a liquid whose refractive index differs from that of the liquid. Prove that, if the glass plate has parallel sides, for any angle of incidence the emerging ray will be parallel to the incident ray.

6. A ray of light passes obliquely through the glass wall of a tank. Prove that the direction which the ray takes as it emerges from the tank does not depend on *either* the thickness of the glass or on its index of refraction. (In other words, show that the direction taken by the ray is the same as if the ray were to go directly from water into air.)

7. In an early attempt to explain why a ray of light is deviated toward the normal when it enters a pond of water it was suggested that the particles of light are attracted more by the water than by the air since water is denser than air . Explain what this would predict as to the velocity of light in water compared to that in air. How does this agree with observed measurements?



8. Descartes described the law of refraction as follows : From any point *P* on the refracted ray a line is drawn perpendicular to the surface, as shown in Fig. 5. This line will cut across the direction of the incident ray at some point *Q* and reach the surface at point *R*. Descartes stated that the ratio of the length *PR* to *QR* is a constant for any angle of incidence. Prove that this agrees with Snell’s law.

CENCO CATALOG NOS. OF APPARATUS

Refraction Apparatus, No. 85555
Transformer, 6 volts, No. 80305-1
Incandescent lamp, 6 volts, No. 84420-22
Miniature Receptacle, No. 84165