Newtonian Particle Theory of Light

by

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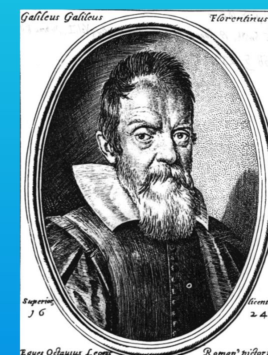

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Light refraction is a common phenomenon that is readily observed with the naked eye. Yet a mathematical formula to describe the effect was only realized in the early 17th century.

In terms of the modern-day quantity refractive index n, Snell's result is:

$$n_1 \sin\Theta_1 = n_2 \sin\Theta_2,$$

where Θ_1 and Θ_2, are the respective angles of incidence and refraction as light passes from one medium to another.

Diagram showing the refraction of light at an interface between air and water. The was viewed by Newton as a clear application of his Second Law of Kinematics, according to which the component of the photon momentum p_i parallel to the interface must be conserved.

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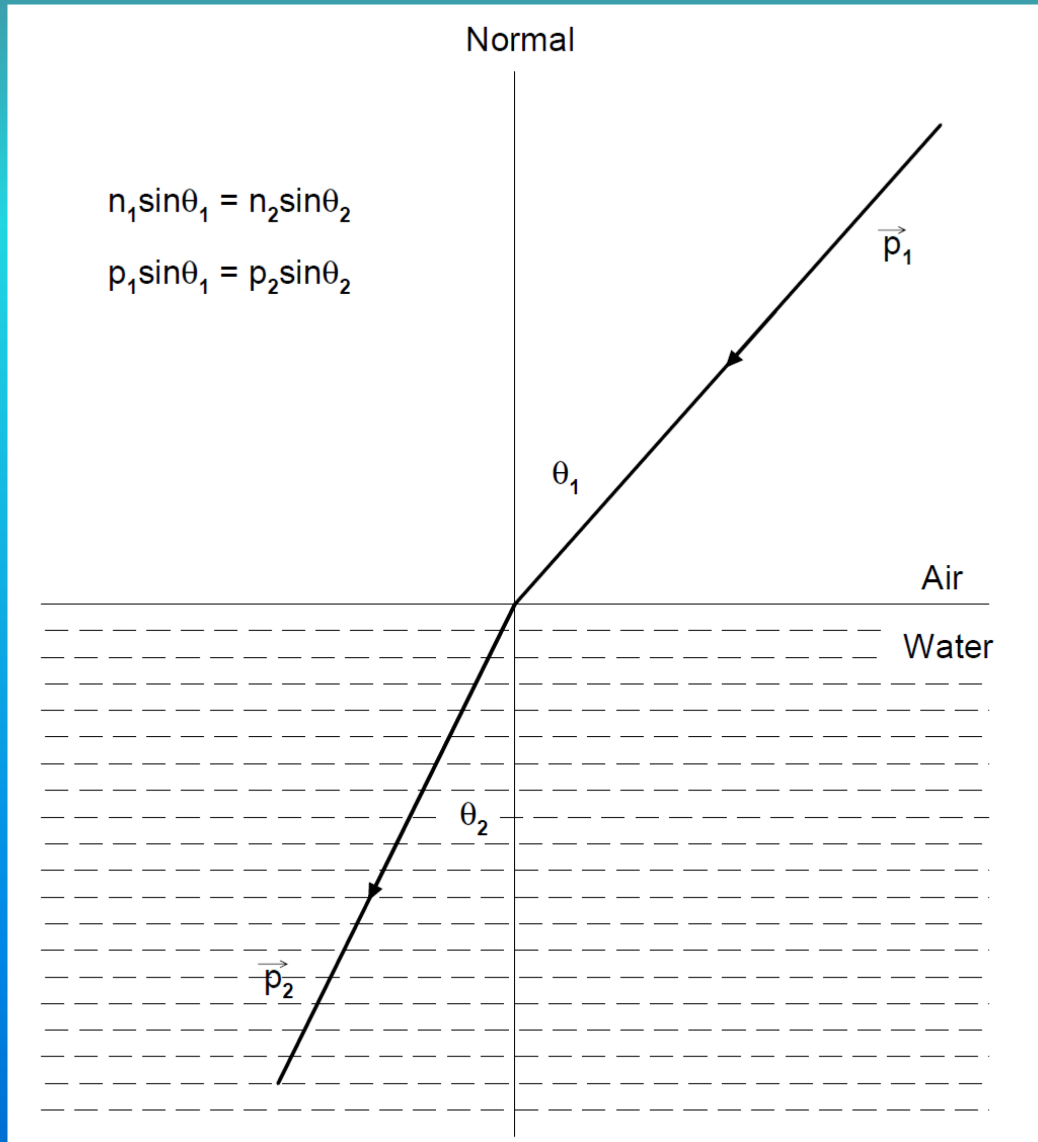
Normal
$n_1 \sin\theta_1 = n_2 \sin\theta_2$
$p_1 \sin\theta_1 = p_2 \sin\theta_2$
$\vec{p}_1$
θ_1
Air
Water
θ_2
$\vec{p}_2$

It was assumed that the light rays travel in straight lines within each medium, and thus there can be no unbalanced forces in either region. Rather, it is caused by a force **F**=d**p**/dt which is normal to the interface. Accordingly, the momentum p in the tangential direction must be conserved. Hence, he concluded:

$$p_1 \sin\Theta_1 = p_2 \sin\Theta_2.$$

By combining these two equations, he arrived at a proportionality between momentum p and index of refraction n:

$$p_1/p_2 = n_1/n_2 = \sin\Theta_2/\sin\Theta_1.$$

The above conclusions are based on Newton's assumption that light is composed of particles. He called them corpuscles, but we now use the term G. N. Lewis coined, namely photons.

The alternative theory was proposed by Huygens, his contemporary critic, who argued that light is made up of waves. He also pointed out a connection with refractive indices in his theory, namely that the wavelength λ is inversely proportional to n.

$$\lambda_1 n_1 = \lambda_2 n_2$$

Huygens also made a prediction about the speed v of light in a refractive medium. He argued that since the speed of light in free space is equal to the product of frequency ν and λ, it follows that the speed in a medium was also inversely proportional to n.

$$v = c/n.$$

Newton's theory predicted the exact opposite, namely,

$$v = nc.$$

He reasoned that since p is proportional to n in his theory, so also would v have to be. He therefore predicted that when a light ray enters water from air, it would speed up, whereas Huygens claimed that it would slow down instead.

History shows that Newton's arguments were accepted by the majority of physicists well into the 19th century.

In 1850, however, Foucault measured the speed of light in water. He found that it decreased as the light entered water from air, in undeniable contradiction to Newton's prediction. On this basis, the view of physicists shifted decisively, and a broad consensus was reached that light was indeed composed of waves and not particles.

The victory of the wave theory was shown to be less than complete, however, when in 1887 it was shown by Michelson that the c/n prediction was not completely verified either. Instead, it was found that there is a correction term which depends on the derivative of the refractive index with respect to the wavelength of the light:

$$v_g = c/n_g = c/n + (\lambda c/n^2)\, dn/d\lambda$$

The correction term has been explained in terms of dispersion effects that are well known from Rayleigh's theory of sound. Beats are shown to arise when sound waves of different wavelength are allowed to interfere. So it was assumed that an analogous effect occurs for waves of light.

Einstein effectively resurrected the corpuscular theory of light in 1905, however, with his explanation of the photoelectric effect. He argued that the finding by Milliken that a definite threshold for the frequency of light is required to produce the emission of electrons from a metal surface was not consistent with the belief that light is composed of waves. The latter should be capable of accumulating energy from light of lower frequency to enable the electron emission, but such behavior is not observed. Einstein's interpretation caused much consternation among contemporary physicists, most notably from Max Planck.

Before going further, let's go back and recall some facts about the Newton-Huygens dispute. Newton argued on the basis of his theory that the momentum p of the particles of light is directly proportional to n, whereas Huygens found experimentally that the wavelength λ of light waves is inversely proportional to n. Combining these two assertions, one arrives at the following conclusion, namely:

$$p \lambda = \text{Constant (for all } n\text{)}.$$

The above relationship is very important in quantum mechanics. It is attributed to de Broglie. In that case, the constant above is given explicitly and has a value of $h = 6.625 \times 10^{-34}$ Js. It is of course known as Planck's constant. The above equation was first reported by Stark in 1909 for light in free space.

There was another key development in 1830 due to Hamilton, however. He introduced a set of Canonical Equations, one of which gives the following relationship for the speed v of an object:

$$v = dE/dp.$$

It can be derived quite simply from Newton's Second Law of Motion.

$$dE = Fdr = (dp/dt)\, dr = dp\, (dr/dt) = vdp.$$

Newton had concluded 130 years earlier in Opticks that the speed c of light waves in free space must be the same for all wavelengths. On this basis, by integration of Hamilton's equation and setting the constant of integration to zero, one obtains the result:

$$E=pc$$

Newton had concluded that the momentum p of particles of light must be proportional to the refractive index n for all media. On this basis, one can generalize the above equation for light in a medium to:

$$E=pc/n.$$

This allows one to use Hamilton's equation to obtain a general value for the speed of light v_g as:

$$v_g = dE/dp = c/n_g = c/n - (pc/n^2)\, dn/dp.$$

Recall, however, that according to the de Broglie relation,

$$p\,\lambda = \text{Constant (for all } n).$$

Therefore, $dp/p + d\lambda/\lambda = 0$. Hence, by substitution,

$$v_g = c/n_g = c/n + (\lambda c/n^2)\, dn/d\lambda,$$

which is the same as Michelson found experimentally.

Moreover, there is something else that can be learned from these equations. Since $E=pc$ for light in free space, and $c = \lambda\nu$ it follows that

$$E = (h/\lambda)\, c = (h/\lambda)\, \lambda\nu = h\nu,$$

which is Planck's equation showing that the energy of light waves is directly proportional to their frequency ν.

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Planck made his discovery based on his studies of the entropy of blackbody radiation, but the latter discussion shows that it could have been deduced as much as 75 years earlier by combining the conclusions of both the particle and wave theories of light with Hamilton's Canonical Equations.

It is also easy to understand on this basis how Newton made his historical error about the speed of light in refractive media. The definition of mass m is:

$$m = p/v = (nE/c)/(c/n_g) = nn_gE/c^2 = nn_gh\nu/c^2.$$

He made the false assumption that the mass of his corpuscles was the same in all media, whereas the above arguments show that it is actually proportional to the square of the refractive index. As a result, p can increase at the same time that v decreases.

The formula for the so-called group refractive index can also be obtained directly from the E=pc/n relation, namely as:

$$n_g = c/v_g = d\,(pc)/dE = d(nE)/dE = n + E(dn/dE) = n + \nu(dn/d\nu)\ .$$

In summary, when one uses the correct definition for velocity (Hamilton's equation), Newton's corpuscular theory is found to be in quantitative agreement with experiment, including Focault's determination of the speed of light in water.

At the same time, the wave theory is found to be deficient because it fails to account for the additional wavelength term in the experimental formula. Its attempt to explain away this error in terms of dispersion effects on the light waves as they enter water is also questionable, as will be **shown** in the following discussion.

Rayleigh pointed out that the correction term could be explained in a similar manner as for sound waves. When waves of slightly different frequency $\omega + \Delta\omega$ and $\omega - \Delta\omega$ are superimposed, the result is a succession of wavelets with variable amplitude A. The corresponding wave function is ($k=2\pi/\lambda$ and $\omega = 2\pi\nu$):

$$\Psi = 2A \cos(\omega t - kx)\cos(\Delta\omega t - \Delta kx).$$

The amplitude distribution curve moves with speed $v_g=\Delta\omega/\Delta k$, which is referred to as the group velocity. For light waves $\omega = kc/n$, so differentiation gives the correct equation with the wavelength dependence found experimentally.

To justify this approach, one has to assume that monochromatic light from free space enters a transparent medium such as water, i.e. where no absorption occurs, two things must happen:

1) Waves of slightly different ω and k values are always formed and

2) It is the speed of the resulting wave groups that is determined in experiments that measure the speed of light in the medium.

There are problems with this interpretation, however. For example, unlike for sound waves, the $\Delta\omega$ and Δk quantities have never been observed for light waves. Does this mean that such differences are just too small to be detected? If so, how can one measure the speed of the wave groups in actual experiments when their period ($2\pi/\Delta\omega$) and wavelength ($2\pi/\Delta k$) are essentially infinitely long?

Moreover, it needs to be explained why the phase velocity ω/k, i.e. c/n, is never observed?

Nothing like this is known for sound and water waves. For example, when two musical instruments are slightly out of tune, both the average tone and the characteristic beat frequency are easily audible. When a rock is dropped into a pond, both wavelets and wave groups are clearly visible.

In short, the supposed "dispersion" of monochromatic light waves as they enter a refractive medium may be purely hypothetical.

In the particle theory, it is assumed all the photons in monochromatic light of a given frequency have exactly the same energy and momentum in any medium. The model assumes that the momentum value increases with n, i.e. E=pc/n, but that the energy is not altered as it passes from one transparent medium to another.

Experimental support for Newton's theory comes from observations of time-correlated single photon counting (TCSPC).

P.L. Muiño, A.M. Thompson and R.J. Buenker, Use of time-correlated single photon counting detection to measure the speed of light in water, *Khim. Fyz.* **23** (2), 117-128 (2004); see also http://arxiv.org, physics/0502100.

The speed of light in water and in air was measured with this technique. Statistical distributions of the photons were obtained as a function of their time of flight over a given distance.

The pattern of these distributions is very similar in these two media. It simply takes longer for the maximum in the distribution to advance through water than through air. On this basis, an accurate value of the ratio of the two speeds was obtained which is in good agreement with the value expected from the dispersion relation.

This experience indicates that individual photons are uniformly slowed as they move into a region of higher n. Furthermore, they continue to move at the same slower speed as long as they remain in the medium.

In summary, the TCSPC experiments show no evidence for the dispersion of light in refractive media which is claimed in the modified wave theory. On the other hand, they are quite consistent with the Newtonian view that all photons in monochromatic light are completely indistinguishable regardless of the medium.

The above discussion shows that that the particle theory of light is quite capable of describing light refraction on a quantitative basis, contrary to what has previously assumed because of Newton's failure to predict the speed of light in water. The question is therefore whether it is possible to explain all experimental observations of light phenomena in terms of such an atomistic theory.

The prevailing view among physicists is that there is a wave-particle duality such that matter behaves as particles in some experiments and as waves in others. This approach was introduced by de Broglie and can be viewed as a compromise between the two theories, but duality is not an intuitive concept and it precludes concrete experimental verification.

It is possible to make a different interpretation of de Broglie's principle, however, which is far more consistent with Newton's views. It relies primarily on the association of a wave with a statistical distribution of many particles: *Some experiments are so precise (photoelectric and Compton effects, the refraction of light and single photon counting) that they reveal the elementary nature of matter in terms of particles, while others (interference and diffraction as the primary examples) are only capable of giving information about the statistical distribution of particles in space and time.*

Support for this statement of the duality principle is found in the Born interpretation of the quantum mechanical wave function Ψ. The absolute square of this function plays a similar role as the intensity in the wave theory of light. In this view, $\Psi\Psi^*$ is a statistical distribution function that gives highly reliable information about large samples of a given entity such as an electron or photon, but is incapable of providing detailed information about the current location of any one of them.

For example, in an interference experiment, if the intensity of the beam is small and detection is made with a device such as a photographic plate, the distribution observed early in the counting procedure will vary significantly from one trial to another.

However, if the experiment is continued for a sufficiently long period of time in each case, the pattern of detected objects will always stabilize to agree completely with quantum mechanical predictions based on the $\Psi\Psi^*$ magnitude for the associated microscopic system.

Most importantly, experiments of this type demonstrate that if the intensity is lowered sufficiently, it is always possible to detect single particles on an individual basis, both for electrons and for photons. This is probably the strongest argument for an atomistic theory of matter and the association of statistical distributions of particles with a quantum mechanical wave packet.

In this view, a single atom, electron or photon is *not* vibrating with a definite frequency and wave length. Rather, the values of λ and ν are the parameters in Ψ that specify the statistical distribution that many identical particles of this kind possess as an ensemble. As in other applications of statistics, *the corresponding distributions may be quite inadequate for predicting the behavior of individuals, but they provide an unerring guide for trends within very large populations.*

The quantum mechanical wave packet thus bears the same relationship to a particle as the histogram does to a member of a sample whose statistical distribution it represents. The latter is a real object, whereas the former is only a mathematical abstraction. A light wave is certainly real, but in analogy to an ocean wave containing many water molecules, it is a collective body whose elementary constituents are single photons.

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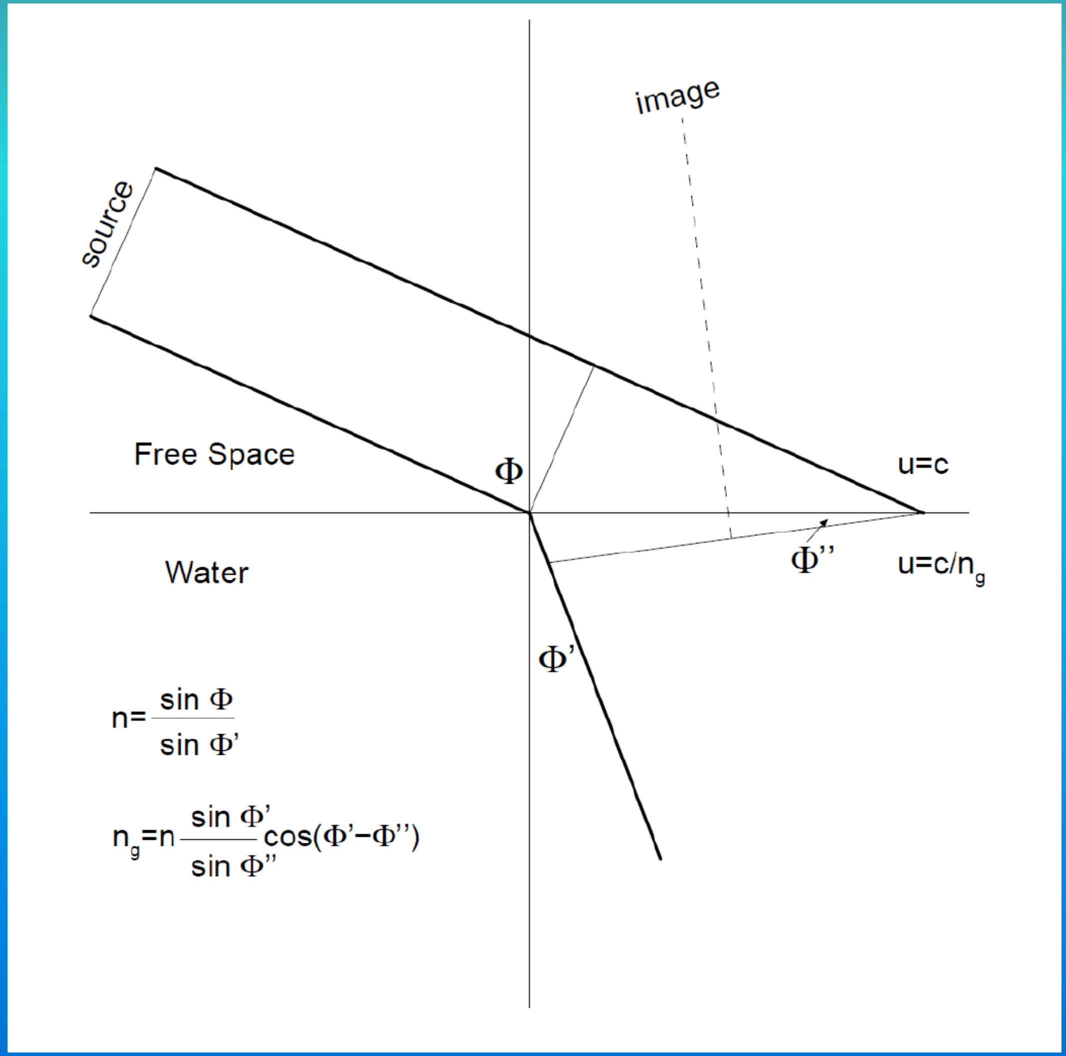

image
source
Free Space
Φ
u=c
Water
Φ''
u=c/n_g
Φ'
n= sin Φ / sin Φ'
n_g=n sin Φ' / sin Φ'' cos(Φ'−Φ'')

The diagram above again shows the angles of incidence Φ and refraction Φ’ as light enters water from free space. The corresponding angle Φ” which the wave front makes with the interface upon entering a refracting medium can be determined experimentally by noting the direction from which the image of the light source is viewed from inside the medium.

The index of refraction of water is defined as n=sinΦ/sinΦ’. Two light rays emanating from the same source are shown as they start out in free space and then cross the interface with water. Depending on the angle of incidence, there is a period of time in which the lower of the two rays is passing through the water while the upper one is still moving in free space. The ratio of the distances that the upper and lower rays travel in this period is clearly the same as that of the corresponding light speeds in the respective media, which in turn is equal to the group refractive index n_g of water.

The fact that the two light rays move at different speeds in water and air for the above period causes the corresponding wave front connecting them to rotate. The effect is exaggerated in the diagram, where the angle of rotation relative to the interface is denoted by Φ”.

It is assumed that the image of the light source *when viewed from within the water* appears to lie along the normal to this wave front, and therefore to be somewhat displaced from the actual position of the light source. The line passing from a suitable detector immersed in the water to the image outside of it also makes an angle Φ” with the normal to the interface, so its value can be determined with relative ease.

The difference between the two angles Φ' and Φ" gives a direct measure of the deviation of n_g from the conventional refractive index n. The exact relation obtained using trigonometric identities is, with n=sinΦ/sinΦ':

$$n_g = n(\sin\Phi'/\sin\Phi'')\cos(\Phi'-\Phi'').$$

The two refractive indices also satisfy the relationship:

$$\cot\Phi'' = (n_g/n\sin\Phi'\cos\Phi') - \tan\Phi'.$$

If Φ'=Φ", it follows from both equations that n_g=n. The latter equality was the underlying assumption of the original wave theory which led to its erroneous prediction of the speed of light in water as the phase velocity $c_i = \lambda\nu$.

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The method described above constitutes a direct determination of the group refractive index for monochromatic light. It does not require a series of measurements involving different wavelengths of light that allows the determination of $dn/d\lambda$. It is therefore also a method for determining the speed of light in refractive media. It has distinct practical advantages over the classical techniques first used to determine this quantity, as well as the TCSPC procedure involving single-photon counting discussed above.

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There are also significant reasons of a more fundamental nature for applying this method for determining light speeds. First of all, it is expected to provide valuable new physiological insight concerning the way in which the human eye and other mechanical devices determine the direction from which the images of objects are perceived to come.

At the same time, it should provide verification for the conclusion that light rays are not actually bent as they pass by a massive body such as the Sun. Instead, they travel in perfectly straight-line trajectories with varying speeds depending on their separation from the body, thereby causing a rotation of the associated wave front.

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