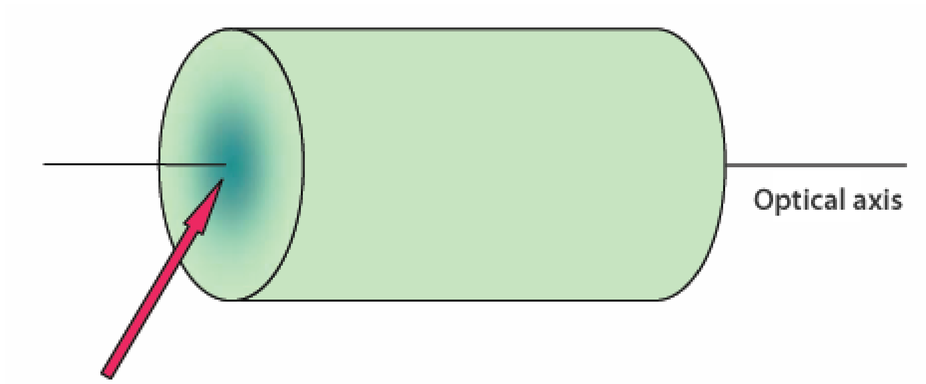
Tapestry of Rays – The Misconceptions Series (2)

Does a light ray bend or not?

When looking at the refraction of light on the lens surface in a picture of a light ray, we are inclined to think that a light ray is bent by the refractive index. In other words, we get the impression that the refractive index itself acts upon the light ray. Therefore, the following question comes to mind.

A graded index lens is shown in Figure 1. The refractive index distribution of the cross-section is symmetrical to the optical axis. On the other hand, in the cross-section including the optical axis, the refractive index is constant in the thickness direction of the lens; namely, it is a perfect cookie cutter structure.



Refractive index distribution in the cross-section is symmetrical to the optical axis.
Cookie-cutter structure in the optical axis direction.

Figure 1

Here, a light ray enters from the left, parallel to the optical axis of the lens. The refractive index sensed by the light ray depends upon the placement of the entrance; however, the light ray does not bend because it enters the entrance face normally. What about after it enters the lens? The refractive index of the lens along the light ray maintains the same value due to its cookie-cutter structure. If this is so, however, does it not seem that the light ray never bends? (See Figure 2)

Light rays never bend?

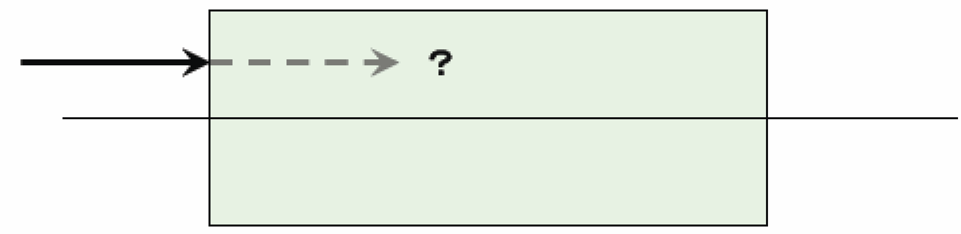


Figure 2

The cause of this misconception is the fact that the following is not recognized; the light ray bends not because of the refractive index, but because of the gradient of the refractive index. To be noted, the light ray equation expressing the behavior of a light ray in an arbitrary refractive index distribution takes the following form (concerning how to derive this equation, see 3.1 to 3.2 of “Principles of Optics”, by Born & Wolf):

$$\frac{d}{ds}\left(n\frac{dr}{ds}\right) = \mathrm{grad}\, n$$

In the above equation, r denotes the position vector on the light ray, s denotes the small length along the light ray, and n denotes the refractive index.

This equation is similar to the equation of motion of a mass point in a gravitational field. Incidentally, this motion equation is, denoting mass by m, the position vector of the material point by r, and the potential energy by U:

$$m\frac{d^2r}{dt^2} = -\mathrm{grad}\, U$$

A material point in a gravitational field continues moving in the direction of the gradient of the potential energy toward the lower side (since there is a negative sign on the right-hand side); however, the light ray bends in the direction of the gradient of the refractive index toward the higher refractive index side. In other words, the refractive index is the potential, and the gradient of the refractive index becomes the force that bends the light ray. In the graded index lens found in Figure 1, the refractive index is graded across its face. Therefore, it is impossible for a light ray to enter the lens without bending. In the structure described in Figure 1, since the gradient becomes positive toward the optical axis, light rays are bent toward the optical axis as a matter of course (Figure 3).

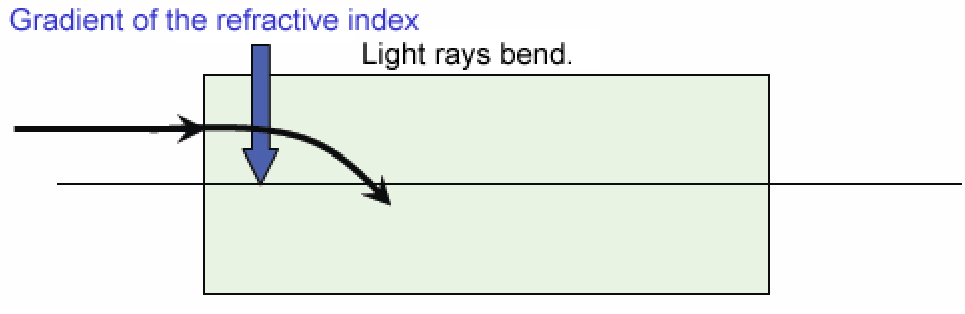


Figure 3

To add another point, it can be said that the concept of a “light ray” is the cause of this misconception. The concept of a “light ray” is an expedient concept, ignoring the uncertainty principle completely. Therefore, it does not exist as an entity in actuality. Since the actual light always possesses wavefronts which expand to a certain degree, it senses a refractive index gradient naturally and the wavefronts deform (sway) according to the gradient. Therefore, we can understand that a light ray that is normal to the wavefront also bends in conjunction with this. By considering it in this way, we can comprehend it, even without knowledge of the light ray equation. However, when we try to think using only the concept of a light ray, a misconception such as in Figure 2 arises.