

The scallop's eye—a concave mirror in the context of biology

Giuseppe Colicchia, Christine Waltner, Martin Hopf and Hartmut Wiesner

Physics Education, Ludwig-Maximilians University, Munich, Germany

Abstract

Teaching physics in the context of medicine or biology is a way to generate students' interest in physics. A more uncommon type of eye, the scallop's eye (an eye with a spherical concave mirror, which is similar to a Newtonian or Schmidt telescope) and the image-forming mechanism in this eye are described. Also, a simple eye model, which can easily be constructed and used in physics classes, is presented.

Introduction

When physics education manages to connect with students' interests it can generate a long-term individual interest and therefore a lifelong openness to science [1]. Colicchia [2], for example, has developed and evaluated physics instruction in the context of medicine and biology. Classes with a medical and biological context were significantly more interesting for students than classes using a more traditional approach. Also, teachers felt that classes with elements from biology or medicine were more interesting to teach than the ones they usually taught. One biological context in which to teach introductory principles of optics is the physics of the eye. We have presented some examples of how to teach the physics of refraction with different eye models in previous issues of *Physics Education* [3–5].

In this article, we present a more uncommon type of eye, the scallop's eye, an eye with a spherical concave mirror, which is similar to a Newtonian or Schmidt telescope. We also present a simple eye model, which can easily be constructed and used in physics classes to teach the physics of concave mirrors.

The scallop's eye

Mirrors and lenses alter the direction of light rays, and so can be used to create images. In a human eye, the lenses and fluids provide an optical path which focuses on the retina images of objects at many different distances. In a scallop's eye, a concave mirror in the optical system creates an image on the retina.

Scallops have usually 40–60 small (1 mm) rather beautiful eyes peeping out between the tentacles of the mantle that protects the gap between the two shells [6, 7]. The eyes point in every direction (figure 1).

The scallop's eye has a single chamber. There is a lens of sorts and behind this a thick two-layered retina filling the space between the lens and the back of the eye.

Superficially, the eye looks quite like a fish eye. However, there is no space between the lens and the retina. The lens ($n = 1.42$ relative to air, $n = 1.065$ relative to sea water) has very little refractive power [8]. With a corneal radius of about $150\ \mu\text{m}$, the lens on its own would form a very deep-lying image, well behind the back of the eye (figure 2). There is no way that the scallop's eye could work in the same way as an eye with a fish lens.

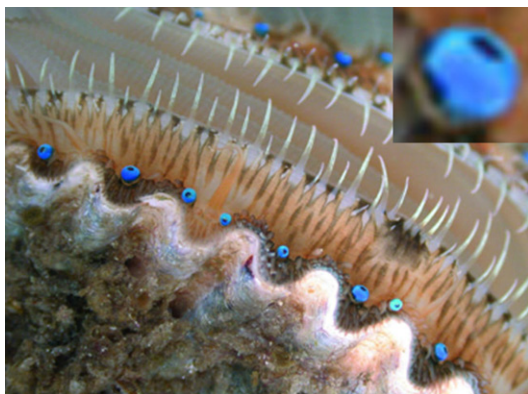


Figure 1. Close-up view of the brilliantly iridescent blue eyes of a scallop. (Picture by Dr W Capman, Minneapolis, Minnesota.)

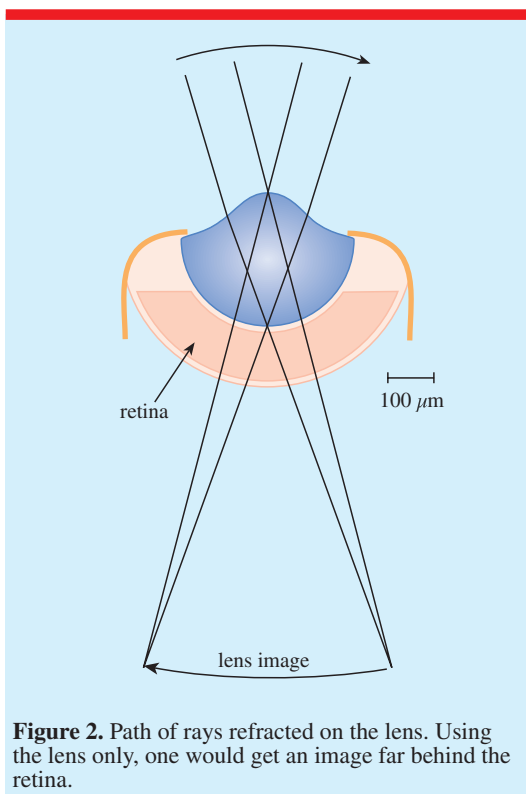


Figure 2. Path of rays refracted on the lens. Using the lens only, one would get an image far behind the retina.

The image-forming mechanism in a scallop's eye

The back of the scallop's eye is spherical (with radius $r \approx 410 \mu\text{m}$) and lined with a reflecting mirror [9], the argentea, so named for its silvery appearance. Natural mirrors are not actually metallic, but are made of multilayers of material

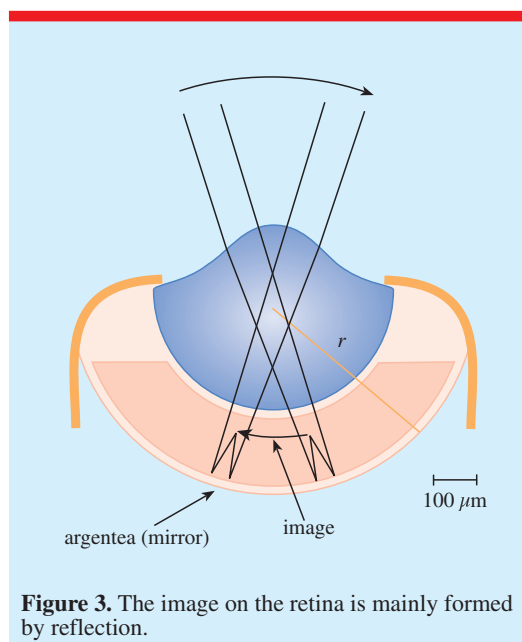


Figure 3. The image on the retina is mainly formed by reflection.

with alternating high and low refractive indices which produce significant reflection as a result of interference.

Spherical concave mirrors form images on the same side of the reflecting surface as the object, and they have a focal length f equal to half the radius of curvature, $f = r/2$. This means that the image of a distant object will be situated half a radius of curvature in front of the mirror (figure 3). The reflecting argentea forms an image just below the back surface of the lens; this is the region occupied by the photo-receptive parts of the retina. Thus this is an eye based primarily on a mirror, not a lens.

In the scallop's eye the focal point is actually a little nearer to the mirror than it would be without a lens, because the lens slightly converges the light. One might ask why this eye has a lens at all. The probable function of the dome-shaped lens is to correct the spherical aberration of the mirror. Just like spherical refracting surfaces, concave mirrors suffer from spherical aberration (over-focusing of rays at a distance from the axis).

The eye of a scallop is a very efficient light-collecting system. Relative aperture is a measure of the ability of an eye to concentrate light on the retina. It can be expressed as the F -number of an optical system, which is the dimensionless ratio of the focal length of the system to the diameter

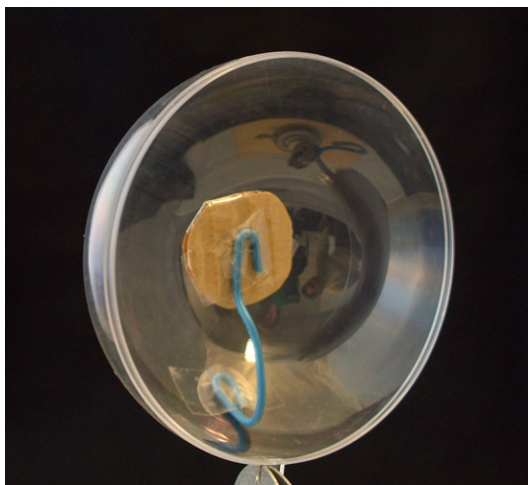


Figure 4. The scallop eye model.



Figure 5. Image on the 'retina' of the scallop eye model.

(D) of the pupil. Assuming that the argentea is a perfect reflector, for a typical scallop's eye $F = f/D = 205 \mu\text{m}/450 \mu\text{m} = 0.5$. For comparison, the F -number of the human eye varies from about 2.5 in dim light to about 8.5 in bright light; that of a fish eye is about 0.8, and that of a good camera is 1.4.

Scallop eye model

To discuss the scallop's eye in a classroom, it is usually helpful to have a hands-on model.

The simple eye model is half a transparent plastic sphere of 6 cm radius, in which a circular piece of white paper fixed at a carton is placed at about 3 cm from the middle, representing the retina (figure 4).

Scallop eye models can also be constructed with any spherical or parabolic mirror, often used in school laboratories.

Functionality of this eye model

To show the functionality of the scallop eye model qualitatively, it works best to hold the eye model in front of luminous objects. You observe the image on the circular white paper representing the retina (figure 5). The sharp image of the luminous object is upside down.

Changing the object distance by only few centimetres makes the image on the 'retina' become blurred. Creating sharp images with a mirror, over a range of distances, would

require accommodation, i.e. a changing radius of curvature of the mirror.

The optics of this eye model are similar to those of a reflecting telescope, except the telescope has a small plane mirror located at the focus of the spherical mirror which redirects light to a detection system (the eye or a CCD camera).

Scallop eye model with a webcam

The eye model can also be constructed with a webcam that is connected to a computer. The photo-sensitive elements of the webcam's CCD sensor are placed in the focus of the eye model, to represent photo-receptors in the retina. To enable students to view the image focused on the CCD sensor, project it onto a screen using a beamer (figure 6).

The distance between the object and the eye model should be a few metres, in order that the size of the image fits with the size of the CCD sensor (1 cm^2). The ideal webcam in this case is small and its CCD sensor is as big as possible.

In figure 6, the image turns up twice on the screen. This is because the light is reflected at both the inner and outer surfaces of the plastic sphere.

To eliminate the reflection of the second surface, the back of the model is covered with a half plastic sphere that is filled with water (through a small hole). The image on the screen is then singular (figure 7). 50% sugared water ($n = 1.4$) can optimize the effect. Another way of reducing

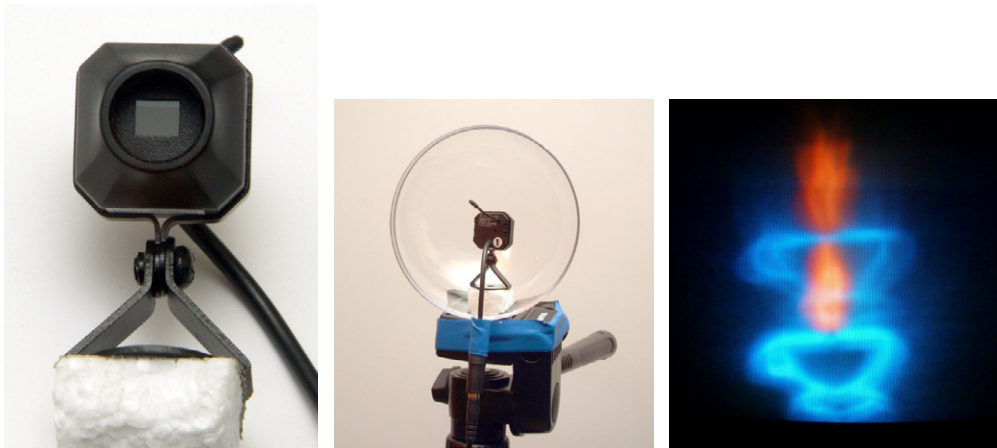


Figure 6. CCD sensor of the webcam without objective (left), the webcam in the eye model (middle), and the image on the screen of the computer (right).

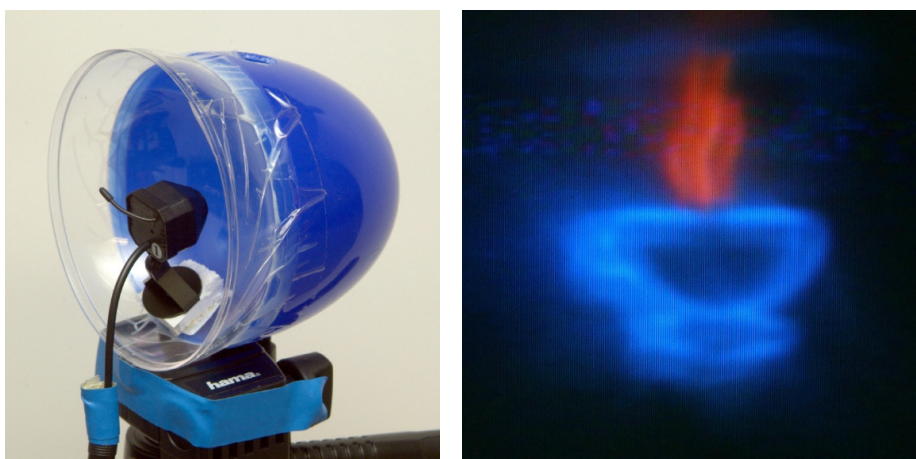


Figure 7. Covered eye model (left) and the image on the screen (right).

the visibility of the second image is to roughen the surface of the plastic sphere, for example, with sandpaper.

Discussion

The advantage of the scallop's eye is its compactness and high light-gathering power, but its mirror optics do have a very serious weakness: the eye inevitably produces a low-contrast image. The light reaching the image has already passed through the retina unfocused before the mirror returns it as a focused image. Moreover, the scallop's eye cannot focus objects located at different distances. Thus, it forms poorer images

compared to the more sophisticated eye of other aquatic animals.

However, considering that a scallop moves slowly compared to a fish, long-range vision is of little use to scallops.

The whole animal reacts to the presence of moving objects by closing itself up. Its eye can sense, at ecologically meaningful distances, the movement of shadows cast by approaching predators, such as starfish or sharks. That is why scallops probably have a simple, rather than a complex, energy-consuming eye. Moreover, its poor optics save the scallop from spending most of its life responding to everything in its visual field.

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