A Resource for Using Real-World Examples in the Physics Classroom

Janelle Van Dongen and Georg Rieger

Citation: Phys. Teach. **51**, 105 (2013); doi: 10.1119/1.4775533
View online: http://dx.doi.org/10.1119/1.4775533
View Table of Contents: http://tpt.aapt.org/resource/1/PHTEAH/v51/i2
Published by the American Association of Physics Teachers

A Resource for Using Real-World Examples in the Physics Classroom

Janelle Van Dongen and Georg Rieger, University of British Columbia, Vancouver, BC, Canada

Physics Teaching for the 21st Century (://c21.phas.ubc.ca) is a free online resource for teachers who are interested in teaching physics concepts in real-world contexts. The materials on this site were developed by a team of physics faculty and graduate and undergraduate students at the Department of Physics & Astronomy, University of British Columbia, based on issues of great current concern—reusable energy, climate change, and medical advancement. Topics on the website also focus on applications of physics in the natural world around us. There are currently about 70 different topics on the website and it is not possible to justly give a sense of the website in total here. Instead we will present one complete example of the resources available on our website and show how it can be used in the classroom or in lecture. The example discussed here[1] is suitable for a first-year university course and focuses on diffraction through a circular aperture and Rayleigh's resolution criterion by looking at the effect of pupil size on the minimum angle of resolution. The original idea came from reading a book on zoological physics,[2] and a short example was later found in a first-year physics textbook.[3]

Difficult topics such as diffraction are hard to motivate in the physics classroom. Starting with an interesting question and an example set in a real-world context can help to increase students' interest. The article starts with an interesting question that the instructor can use to generate interest: "Why can eagles see more clearly farther away than we can?"

The instructor can then say that part of the answer is due to three "big ideas":[4]

1) Rayleigh's criterion expresses a condition for when two point sources will be resolvable based on diffraction through a circular aperture.
2) The pupil is a circular aperture through which light diffracts. Larger pupil size for birds of prey partially accounts for the ability of birds of prey to resolve objects at larger distances than humans can.
3) The density and size of receptor cells (cones) in the fovea of the eye roughly matches diffraction effects so that we are not limited by a lack of receptor cells, nor is there a waste of cones by having much more than is needed. Birds of prey have higher cone density to match the smaller diffraction spots that arise from their larger pupil size.

Each of the three points needs a careful explanation, which is provided by the online article. The instructor should start with a visual representation of the eye (Fig. 1) so that the students can see how light entering the eye is focused onto the retina. A minimum knowledge of ray optics is assumed here.

Figure 1 has some detail that the instructor does not need for the discussion. The points to make are:

– Light enters your eye through your pupil and is focused to a spot on your retina where the light is absorbed and transformed into electrical signals that are conducted to the brain.
– From ray optics we know that the eye lens focuses light from a particular point on an object to a corresponding point on the image at the retina.

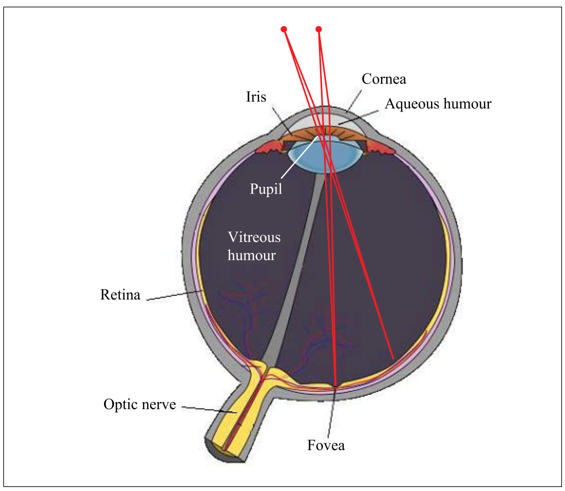

Fig. 1. The human eye.[5] Light entering the eye from two point sources shown is focused onto the retina. The focusing occurs mostly due to refraction at the cornea. Point sources that you are directly looking at get focused onto the fovea. Point sources off to the side are focused outside of the foveal region.

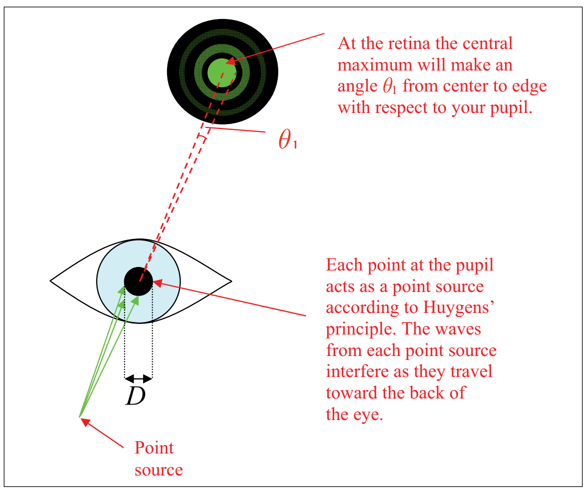

Fig. 2. Light from a point source is diffracted by the pupil. As a result the light being focused onto the retina is not a perfect point but consists of a central maxima and rings. Note the picture is not to scale.

DOI: 10.1119/1.4775533

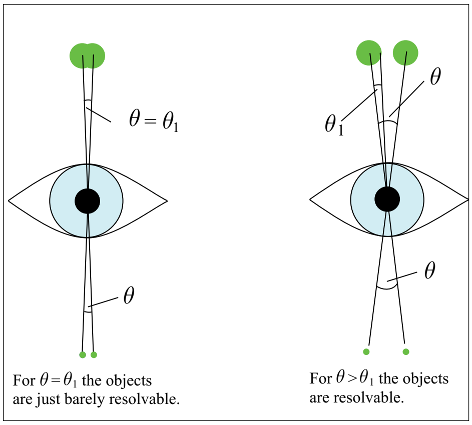

Fig. 3. Light from two point sources (bottom) enters your eye, making an angle θ with respect to your pupil. Two central maxima (top), due to the diffraction of light entering the pupil, fall on the retina at the back of the eye, also subtending an angle θ at your pupil. The angle subtended by a central maximum from center to edge is θ_1. According to Rayleigh's criterion, the point sources are resolvable if $\theta \geq \theta_1$.

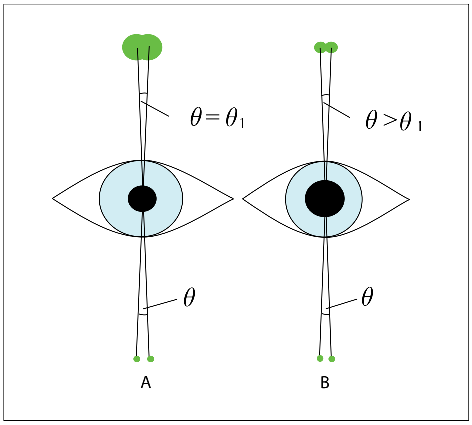

Fig. 4. The angle θ two point sources make with respect to your eye is determined by the separation between the point sources and the distance to your eye. The minimum angle of resolution θ_1 is inversely proportional to pupil size. For a pupil size (case A) where the point sources are barely resolvable, the point source would still be resolvable for a larger pupil size (case B).

– It turns out that we cannot see arbitrarily small details on an object. The limitation is due to diffraction, the density of photoreceptor cells (called "cones") at the center of the fovea (called the "foveola"), and lens and cornea aberrations. Figure 2 shows qualitatively what happens when light passes through a circular aperture.

At this point, we suggest that the instructor remind students of the diffraction pattern that is obtained in the case of single-slit diffraction (assuming that this has been covered in class before) and compare it to the case of a circular aperture: Instead of straight fringes, diffraction rings are obtained. Without going into more detail, the results can then be summarized as follows:

The pupil in your eye is a circular aperture and light passing through it will diffract, forming a central maximum surrounded by diffraction rings (Fig. 2). The angle the central maximum makes from center to edge with respect to your pupil is[6]

$$\theta_1 = \frac{1.22\lambda}{D}, \tag{1}$$

where λ is the wavelength of light from the point source (we are assuming the light is monochromatic) and D is the diameter of your pupil. θ_1 is in radians; λ and d are in meters.

Many students will not see the connection between the angle in Eq. (1) and the size of the image on the retina. At this point, the instructor could ask the class a few questions such as:

– Where is the image formed?
– How far away is the retina from the pupil?
– How large is the human eye?

Again, a comparison to the case of single-slit diffraction is probably helpful here.

Depending on the level of the class, the instructor can discuss that the wavelength of light, λ, changes once it enters the eye. The wavelength of light inside the eye is λ_{eye} and we will take the index of refraction of the eye to be roughly that of the vitreous humour ($n = 1.33$)[7] so that

$$\lambda_{eye} = \frac{\lambda_{air}}{1.33}. \tag{2}$$

At this point the instructor could summarize by saying that even a microscopically small point is imaged as a small disk of a certain size, and this has consequences for how well we can distinguish small details, such as two points very close together.

Ray optics tells us that the angle θ that two sources make with respect to your pupil is equal to the angle that the two central maxima make with your pupil. Rayleigh's criterion states that if the angle θ is greater than θ_1, then you will be able to resolve the two points (Fig. 3).

Here the instructor should remind the students where the angle θ_1 is coming from: that it is due to diffraction and given by Eq. (1). Now the class is ready to complete the second "big idea." Birds of prey such as the eagle, owl, and hawk are known for their remarkable ability to see clearly at large distances. Their eyes operate along similar principles as our eyes; however, these birds have a larger pupil size compared to humans for the same light conditions.[8] For example, humans have a typical pupil diameter of 2.5 mm, whereas the bald eagle, great horned owl, and red-shouldered hawk all have pupil diameters of 9, 15, and 8 mm, respectively, for the same light conditions.[8] Having a larger pupil size means that the minimum angle of resolution θ_1 is smaller (Fig. 4). This means that for a fixed separation between the point sources, the point sources can be further away and still resolvable for a larger pupil size.

Finally, the instructor can follow up by pointing out that diffraction is only one effect that determines eye sight resolution. The density and size of the cones is also of fundamental importance. The diameter of the cones in the foveola in humans[9] is around 2.5 μm, and they are densely packed so they are touching. For a distance of 2 cm from pupil to the retina[10] and taking green light (550 nm) and a pupil size of 2.5 mm, the spot size of the central maximum would be approximately 5 μm. At roughly 5-mm pupil size, the diffraction spot size matches the cone size. Our pupil size is typically larger than 5 mm only for dim lighting conditions. This means that the density and size of cones is roughly matched to diffraction effects, with the cone diameter being slightly smaller than the diffraction spot size. An eagle has more densely packed cones, with a cone diameter of 1.6 μm, and a longer distance from pupil to retina[10] of approximately 3 cm. Again the cone diameter roughly matches the central maximum size due to diffraction.

Aberrations in our lens and cornea prevent there from being a gain in visual acuity due to an increased pupil size beyond our typical pupil sizes of 2.5–5 mm.[11] Eagles are able to take advantage of larger pupil sizes and higher cone density because they have a clearer cornea and lens,[12] and they can change the shape of both their cornea and lens, allowing for fine focusing.[13]

As an alternative to the lesson/lecture outlined above, the online article could be assigned as pre-reading for the class. In class the teacher could summarize the main points using a set of PowerPoint (or PDF) lecture notes also provided on the site. The online site has several resources associated with this article:

1) Multiple-choice or "clicker" questions that could be used in class to test the understanding of students using questions such as:

"As two points on a piece of paper are moved toward you, how does the angle the points make with respect to your eye change?"

a) no change
b) smaller
c) larger.

"What wavelength of light would you be able to resolve at the furthest distance based on diffraction?"

a) red
b) green
c) blue.

"How does the width (W) of the central maximum formed from diffraction through a circular aperture (pupil) change with aperture size (D) for a fixed distance away from the aperture?"

a) W increases as D increases.
b) W decreases as D increases.
c) W does not depend on D.

2) Problem sets that can be used as homework or as an in-class worked example asking, based on diffraction, how far away a student with a pupil diameter of 2.5 mm would be able to resolve two point sources 0.5 cm apart versus an eagle with pupil diameter of 9 mm, for a wavelength of 550 nm.

3) A take-home experiment that asks students to draw two felt marker lines of a certain color on a piece of paper parallel to each other and a certain distance apart. The students are then asked to determine the distance from the lines that they can still resolve the lines and compare that to the prediction based on Rayleigh's criterion. Possible reasons why the two would not be similar based on both experimental error and imperfections in the eye are also asked for and discussed in the solutions.

The solutions to the problem sets, multiple-choice questions, and take-home experiments are also available on the website.

The example article here is intended for the first-year university level, but the site also has material suitable for junior and senior high. One of the collaborating members is a high school physics teacher and has successfully used the articles by assigning each student in his grade 12 class an article and then having the students give a short in-class presentation about the topic.

Acknowledgments

This project is sponsored by the Social Sciences and Humanities Research Council of Canada and the Teaching and Learning Enhancement Fund (University of British Columbia). We gratefully acknowledge the help from current and past members of the c21 team: Kevin Asperin, Shaun Dychko, Andrzej Kotlicki, Theresa Liao, Mathew "Sandy" Martinuk, Jacob McNeil, Oliver Millar, Eric Mills, Rachel Moll, Anoushka Rajan, Oren Rippel, Angela Ruthven, Edson Sanchez, Brittany Tymos, Christian Villar, Susanna Waltham, Chris Waltham, and Claire Wheeler, and Chenchong Zhu.

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Janelle Dongen *is a PhD candidate in experimental physics with a specialization in atomic physics. She is also interested in physics education research and a member of the Physics Outreach group in the Department of Physics and Astronomy at UBC.*

Georg Rieger *is a lecturer with a background in optical spectroscopy. He is now interested in physics education research and a member of Physics Outreach. He is also the department director of the Carl Wieman Science Education Initiative.*
University of British Columbia, Department of Physics and Astronomy, Vancouver, BC V6T 1Z4, Canada; rieger@phas.ubc.ca