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Christopher Sirola
University of Southern Mississippi, Christopher.Sirola@usm.edu

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Joe Heafner, **Column Editor,** Science Department
Catawba Valley Community College, Hickory, NC 28602; heafnerj@gmail.com

Galileo's telescope

Christopher Sirola, Department of Physics & Astronomy, University of Southern Mississippi, Hattiesburg, MS 39406; Christopher.Sirola@usm.edu

One of the most consequential inventions of modern times is the telescope. Almost immediately upon turning it to the skies, Galileo made discoveries that altered our perceptions of our place in the cosmos forever: features on the Moon, the rotation of the Sun, the composition of the Milky Way, the phases of Venus, and the four large moons of Jupiter.

One story, perhaps apocryphal, involves a lensmaker from Holland named Hans Lippershey (alternatively Lipperhey) in 1608. Some children wandered into his spectacles shop one day and amused themselves by playing with lenses. After scooting them out of his store, Lippershey reproduced their activities by aligning one lens after another in front of his eye and noted the improvement (in terms of size and clarity) of the resulting image. Word of the new device quickly swept across Europe, including Italy, where Galileo constructed his own model.[1]

How do we get our students to appreciate both the science and the importance of the telescope? In a small lab-based class, this isn't usually an issue—we can have our students conduct experiments in a laboratory setting and allow them to explore lenses and telescopes as much as we wish. But what if one is teaching a large number of students (say, 50 or more) in a lecture-only classroom? Or if one has a class with limited math skills or a class with limited time?

This activity is in the spirit of play of those children four centuries past. The equipment is relatively inexpensive—rulers, calculators, and lenses. Cheap plastic lenses can be purchased through any of several major science supply companies. We will make one small change—Galileo's original telescope used one convex-planar lens and one concave-planar lens, but for simplicity we will use two double-convex lenses, which are easier to work with.

The key property to study in order to construct a working telescope is the *focal length* of each lens. For a simple telescope of this type, the distance d between the two lenses should equal the sum of their focal lengths (see Fig. 1):

$$d = f_o + f_e \qquad (1)$$

where f_o and f_e are the focal lengths of the two lenses. The reasons for the "o" and "e" subscripts will soon be made clear.

Suppose we send parallel light rays into a lens (Fig. 2). A convex lens will converge the incoming parallel rays to the focal point, whose distance from the lens is defined as the focal length. We can use this idea to estimate the focal length: send the light from an extremely distant object (such as the Sun) through the lens such that it makes a bright spot of light, and the distance from the lens to the spot is the focal length.

However, suppose this option is not available—for example, perhaps the class cannot meet outside or a cloudy day prevents us from viewing the Sun. Another way to estimate the focal length of a lens, indoors and without objects at far distances, is to turn around the geometry (Fig. 3).

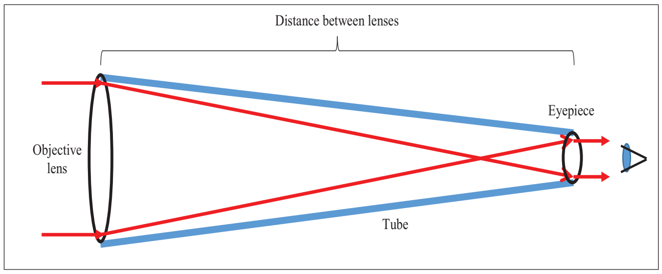

Fig. 1. Basic structure of a refracting telescope.

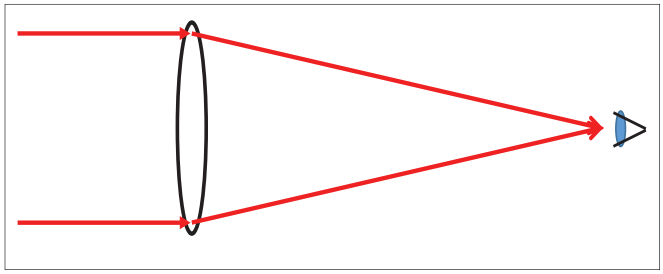

Fig. 2. Parallel rays converge to the focal point after passing through a convex lens. The distance from the lens to the focal point is the focal length of the lens. The result is that the observer sees a focused image.

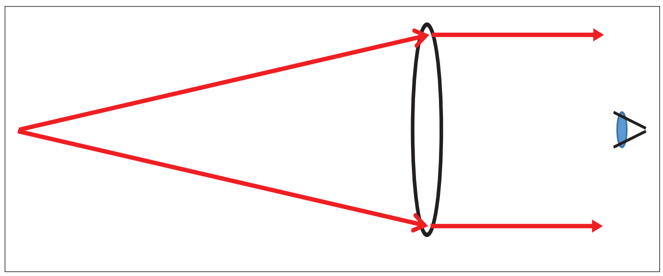

Fig. 3. Rays diverging from the focal distance (in front of the lens) passing through a convex lens emerge as parallel rays. The result is that the observer cannot see any image at all.

In this version of our mini-experiment, a student holds a convex lens in front of her- or himself, looking through the lens at a distant object using just one eye. If the student holds the lens closer to the eye than the focal point, then the image will appear upright. If the student holds the lens further than the focal point, the image will appear upside down. If the lens is held at precisely the focal point, the student will see nothing but a complete blur. This occurs regardless of the background object used by the student.

Some hints for students to perform this task effectively: First, place students in teams (between three to five). One reason is simply to have students assist each other in making and recording measurements—it is difficult to hold a lens stably with one hand and make a measurement of the distance from the lens to one's eye via a ruler with the other hand. A third student can record the measurement for the others. Another reason is that multiple measurements allow the students to calculate an average focal length for each lens, which helps them to achieve a more precise result. Second, it is important to emphasize what we mean by "blur" in this instance. An image seen through the lens can look blurry—i.e., not perfectly focused—even if not exactly at the focal point. From experience, students have a tendency to overestimate the distance from the eye to the focal point, so it is important to give students some extra instruction and attention when performing this task.

Once student teams have determined focal lengths for both lenses, they can "construct" their telescopes. We are not worried about placing the lenses at opposite ends of a tube; instead, simply have each student take turns holding one lens next to an eye and moving the other lens back and forth while looking for a clear image in the middle of the far lens. When this happens, we have our telescope. As an added benefit, students need to determine which lens is which—that is, which lens should be held close to the eye and which should be held far away. In astronomy, the lens furthest from the eye will have the longer focal length and is called the *objective* and the lens next to the eye is the *eyepiece*. The focal lengths can thus be abbreviated as f_o and f_e, respectively.

As discussed earlier, the sum of the focal lengths should be the same as the distance between the lenses. In this type of mini-experiment, we shouldn't expect to achieve a great deal of precision; nevertheless, with careful work on the part of the students, one can expect to get within 10% difference between the sum of focal lengths and the measured distance between the lenses.

Another property of interest for a telescope is its *magnification*. In optics, magnification is simply the ratio of the size of the image compared to the size of the object. Since one of the benefits of using a telescope in the first place is to make an image larger, we want our students to construct a telescope in such a way as to guarantee a larger image.

The magnification m of our telescope is given by

$$m = -\frac{f_o}{f_e}. \tag{2}$$

The negative sign references the fact that the image will appear upside down through our refracting telescope. Galileo's first telescope reportedly had a magnification of – 3; an interesting question for the students is to have them compare their telescope to that of Galileo.

Depending on the needs of your class and time available, you can expand this activity to include questions regarding light-gathering power, resolution, and the proper ways to describe images. We have made a sample activity available.[2] Enjoy your new telescopes, and clear skies!

Reference

1. This configuration of two lenses is called a refracting telescope (or refractor), since it only uses the refractive properties of lenses. The other major type of telescope, the reflector, uses mirrors and was invented many decades later by Isaac Newton. A reflector is more complicated than a refractor, and we are interested in simplicity in this activity.
2. View the activity at *TPT Online*, http://dx.doi.org/XXXXXXXX, under the Supplemental tab.