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Depth Perception

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

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Depth perception

Christopher Sirola, Associate Professor, Department of Physics & Astronomy, University of Southern Mississippi; Christopher.Sirola@usm.edu

In most disciplines, finding the distance from one object to the next is, at least in theory, a simple operation. Not so in astronomy. While the size of Earth itself was determined with a fair degree of accuracy in ancient times, the scale of the solar system wasn't fully understood until just a few centuries ago, and the distances to even the closest of stars wasn't reliably determined until Friedrich Bessel measured the distance to 61 Cygni in 1838.

The reason is fairly obvious—distance scales in astronomy are enormous. It is difficult even sometimes for those who work in the field to have a real appreciation for just how large our universe is. We can't string out a ruler or tape measure between stars, of course, and the notion of flying to another star is the stuff of science fiction. To complicate matters, stars appear as points of light against a dark, featureless background. The solution to this difficulty is the application of a commonplace trick of everyday life.

When my wife, Susan, was younger, her family had a cat. The cat developed an infection in one of its eyes, and while they were able to save the cat's life, they were unfortunately unable to save the eye. The cat seemed fine, with one glaring exception. The poor animal kept bumping into things. The loss of one of its eyes had destroyed its sense of depth perception.

This effect—where one looks at a nearby object from slightly different angles—is called trigonometric parallax, which is often rendered as trig parallax or just parallax for short. You and your students can demonstrate its power through the following simple exercise:

1. ***Pick up*** a small, thin object such as a pen. Hold the pen in front of you, with your arm about halfway extended. Close your right eye and note the apparent position of the pen compared to a distant background (see Fig. 1).
2. ***With the pen's*** apparent position in mind, swap eyes (that is, open your right eye and close your left) and repeat your observation. You haven't moved the pen, yet it appears to have shifted its position relative to the distant background.

The reason this trick works is because your eyes are located at slightly different positions on your head. These different locations allow you to observe the nearby pen from different angles and gives the illusion of the pen having shifted its position. If you carefully measure the distance between your eyes and the angle of the pen's apparent shift, you can use right-triangle trigonometry to calculate the distance to the pen (see Fig. 2):

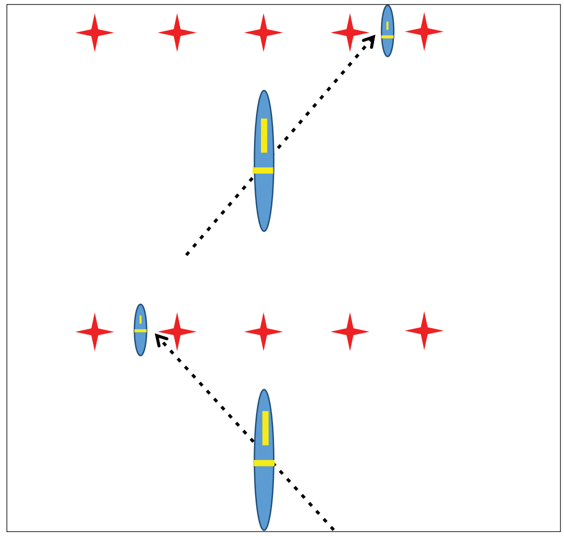

Fig. 1. Hold a pen in front of you. With your left eye, the pen appears to be in one position compared to a distant background (upper figure). With your right eye, the pen appears to have shifted, even though the pen did not move (lower figure).

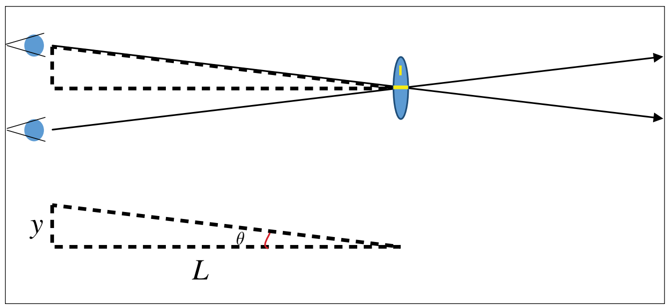

Fig. 2. Construct a right triangle using the distance between the observers (*y*) and the angle of parallax (*θ*) in order to determine the distance to the object (*L*).

$$L = \frac{y}{\tan\theta},$$

where y is the distance between eyes (defined as half of the "baseline"), θ is the angle of parallax (it is defined as half the angle of shift one observes), and L is the distance to the object. I will revise the symbols presently, for reasons you will soon see. Note that the larger the baseline, the larger the angle of parallax.

Depending on your class and the amount of time you wish your students to devote to this exercise, you can either show it simply as a demonstration or, with protractors and tape measures, have students calculate distances to objects. Astronomers apply this trick to nearby stars. In this case, however, the distance between eyes, or even the distance between observatories on opposite sides of Earth isn't large enough. So astronomers use Earth's orbit as the baseline (see Fig. 3).

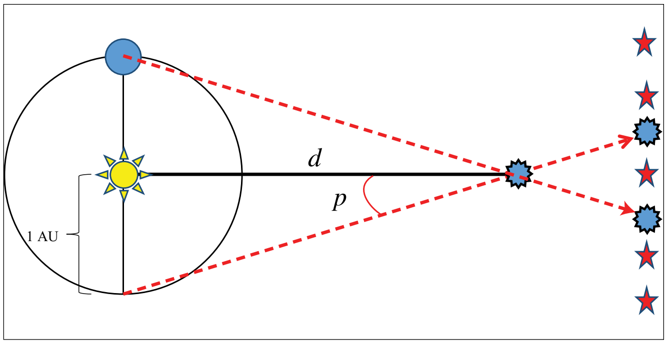

Fig. 3. The orbit of the Earth is used to measure the apparent angular shift in position of a nearby star compared to a distant background. The distance from the Earth to the Sun (1 au) and the parallax angle (*p*) are used to calculate the distance to the nearby star (*d*).

The average distance from the Earth to the Sun is well known—in fact, its specific value was set last year—and represents a commonly used unit in planetary astronomy, the *astronomical unit*. One au is approximately 150 million kilometers, or 93 million miles, itself being an enormous distance for us.[1]

However, even the nearest stars are so far away that the au isn't really that large of a baseline—far smaller, in comparison, than the baseline of one's eyes are for the purpose of not bumping into couches. To better understand the tiny angles involved in stellar parallax, we need to (a) define a smaller unit for angles and (b) use telescopes, as our eyes can't detect such tiny parallaxes.

We are all familiar with a complete circle containing 360 angular degrees.[2] An individual degree is small, but can be handled fairly well by the human eye; for comparison, the full Moon is about half of a degree across. But astronomers (such as Tycho Brahe) who tried to apply parallax measurements to stars soon found this is inadequate. So astronomers subdivide the degree. One angular degree is said to contain 60 minutes of arc[3] (or "arcminutes" for short), and an arcminute is itself split into 60 arcseconds. A full circle then contains just under 1.3 million arcseconds.

Even this tiny unit is insufficient. No stars[4] show a parallax angle as large as 1 arcsecond. The closest known star, Proxima Centauri, has a parallax of 0.75 arcseconds. Standard trigonometry can thus be used to find the distance to a star like Proxima once its parallax is known. Astronomers shorten the procedure with one more new definition. A *parsec* is the distance at which an object shows a *par*allax of one arc*sec*ond, using Earth's orbit to define the baseline. By interesting coincidence, a parsec is on the same order of magnitude as the light-year (specifically, 1 pc = 3.26 ly).[5] The distance to Proxima is then given by

$$d = \frac{1}{p},$$

where p is the parallax in arcseconds and d is the distance in parsecs. With this information, we find Proxima to be 1.33 parsecs, or 4.26 light-years, away. I find it useful to have students express these results in units of miles or kilometers, so they get to see just how large these distances are, and why astronomers find it more appropriate to use parsecs and light-years.

Modern instruments (most recently a satellite named Hipparcos) have pushed parallax precision down to the milliarcsecond (1/1000 of an arcsecond) level, allowing astronomers the ability to reasonably discuss star distances out to a thousand parsecs. To determine distances farther than that, astronomers need to use other methods of measurement.

We have made a sample activity regarding trig parallax available. Enjoy your new sense of depth perception, and clear skies! (author: would you want this to be placed on the TPT website?)

References

1. Earth's orbit is slightly elliptical, so astronomers make appropriate adjustments when applying the parallax method for real.
2. There are some interesting historical reasons for the choice of 360 that lie beyond the scope of this article. A quick hint is to compare this to the number of days in a year.
3. Tycho, the best observer before the invention of the telescope, cited angular measurements to a precision of 2 arcminutes.
4. Always excepting the Sun, of course!
5. And now you know the origin of the biggest astronomical gaffe in cinematic history. Han Solo should be ashamed of himself.