The Parallax Activity

[00:00:00.00]

[00:00:24.96] PROFESSOR BLACK: Hello. My name is David Black, and I teach science and computer technology courses here at Walden School of Liberal Arts in Provo, Utah, USA. One of my favorite subjects to teach is astronomy. And today, you'll be learning a lesson that has one of the central ideas in astronomy, which is how do we measure the distance to stars?

[00:00:48.56] Many centuries ago, people thought that the stars were all the same distance away, that they were simply holes in the sphere of space letting in the celestial light. They were placed in the sky to commemorate the deeds of gods and heroes, such as Heracles or Perseus. Now we know that they are huge balls of fusing hydrogen and helium; that they come in different sizes, colors, and temperatures; that some are single where others are in pairs or more, that they are all different distances from us.

[00:01:18.67] So how do you measure the distance to a nearby star? Obviously you can't use a measuring tape, because your tape would have to be billions of kilometers long. What we do is use something called parallax. Let me demonstrate how it works.

[00:01:32.10] If you were to hold up your finger with both of your eyes open and line it up along some vertical line, let's say the edge of the window, now if I shut one of my eyes, let's say my left eye, my finger seems to still be lined up. If I shut my right eye and open my left, my finger seems to have jumped to the side. Why is that? Go ahead and try this out yourself.

[00:02:15.30] OK. What happened? If you're like me, as you were holding up your finger and you shut your left eye, your fingers stayed on the line. What that means is that you are right-eyed. Just like I am right-handed and right-footed, I also have a dominant right eye. The left side of my brain is dominant compared to the right side, because your brain switches over. That's an example of parallax.

[00:02:42.25] Now let's show you another example of parallax. As we move, nearby objects seem to move more than farther objects. Look at Mount Timpanogos, which is about nine kilometers away. It doesn't seem to be moving as I drive up the interstate. But the fields and buildings next to the freeway seem to be whipping past quickly.

[00:03:01.74] We can judge that the buildings we see are closer than the mountain but further than the billboard signs by how fast they seem to move. Of course, the buildings aren't moving. We are.

[00:03:11.90] The same thing happens when we look at the stars from Earth. Let's have you try this out. In your classroom, have three students stand up.

[00:03:20.01] Have the first students stand in the far corner of the room and have the second students stand in the middle. Then have the third student at the other side of the room walk slowly back and forth. Observe what happens with the apparent position of the first and second student.

[00:03:55.98] You'll notice as the third student walks back and forth, the middle student seems to change position compared to the background student. This isn't that the middle student is really moving. It's that the third student is shifting position and creating a parallax angle, just the way the Earth moves around the sun.

[00:04:12.93] To use parallax to measure the distance to stars, astronomers take advantage of the fact that Earth is constantly changing position as it orbits around the sun. As this animation shows, a star close to us will seem to shift position compared to the

further stars. The closest stars to us are still very far away compared to anything in our solar system, so the parallax shift is very small, less than 1 arc second of a degree. But using telescopes and careful measurements, we can still measure this parallax angle.
[00:04:44.52] Another important idea is that if we draw a triangle using the Earth, the sun, and the nearby star as corners, it will become a right triangle. We can now use trigonometry to figure out the length of the sides and the interior angles. We know the length of one side of this triangle is the distance between the Earth and the sun, which we call one astronomical unit. It is equal to 149,597,871 kilometers. Using that distance and the parallax angle, we can calculate the distance to the nearby star using the tangent function.
[00:05:24.68] But before we try this on stars, let's try something a little bit closer. When surveyors measure distances, they can't always travel to a target spot with their instruments. For example, what if we want to measure the height of Mount Timpanogos? All we need to know is the distance to the base of the peak and the angle to the peak. Then we can calculate its height without having to climb it.
[00:05:48.60] Let's try it out. Finding the distance to Mount Timpanogos is a bit tricky, because I can't get right under the mountain. And it's hard to drive in a straight line. I can be more accurate using a map.
[00:06:01.55] In Google Earth, I can use the Ruler function to find the map distance between two points. Just go to Tools in the menu bar and choose Ruler. Then, click and draw a line between the two points, in this case, the highest peak on Mount Timpanogos and Walden School. I measure it as 11.25 kilometers.
[00:06:22.97] Now that you've had a chance to decide on a local landmark and you've measured its distance on the map, it's time to calculate its height. We'll use this quadrant, which is a meter stick to which we've attached a protractor at the 50 centimeter line. Hanging from the protractor is this string with a weight, which will act as a plumb-bob.
[00:06:43.30] Now, when the meter stick is horizontal, the plumb-bob will read 90 degrees. What we're going to do is figure out how far off of 90 degrees the weight takes us. One of you will hold the ruler sighting in on the top of your landmark while a second person read the angle on the plumb-bob. We can measure the angle to the peak, which works out to be about 12 degrees.
[00:07:07.65] Now let's do our calculations. Here's the mountain that we want to measure. Here's our right triangle. Here is the angle that we measured.
[00:07:16.90] The distance to the base of the mountain is what we call the adjacent side of the triangle from our angle, which is 11.25 kilometers. We want to know the height, which is the opposite side from our angle. The tangent function of our angle is equal to the opposite side over the adjacent side.
[00:07:35.96] Doing a bit of algebra, we can solve for the opposite side. Now let's put our numbers into a calculator. We can solve for that opposite side, which is the tangent of our angle, 12 degrees, times 11.25 kilometers will equal the height of the mountain. I calculate a height of 2.391 kilometers, or 2,391 meters.
[00:07:59.48] Now that's the height of the mountain from its base to its peak. Add in our altitude here at Walden School, which is 1,390 meters, to the height of the mountain, which is 2,391 meters. That gives us a total height for Mount Timpanogos of 3,781 meters. Now checking that on a map, the actual height is 3,581 meters. So you can see that we got quite close.

[00:08:24.85] All right. Now it's your turn. With your teacher, pick a local landmark and see if you can calculate its height.
[00:08:53.84] How did you do? Getting an accurate angle with our simple quadrant isn't very easy. And you have to be careful to make sure you're getting the correct angle. You should estimate the angle visually, and then make sure that your actual angle is reasonable.
[00:09:07.81] Now that you've gotten the idea, let's try out the same technique on our main activity, trying to find the distances to simulated stars. Here's how you're going to do it.
[00:09:18.39] You'll simulate this process using a diagram your teacher has already laid out. You will divide into six teams. And each team will be assigned to one or more planets. Six planets have been laid out in a line around a central star, with Planet 1 the closest and Planet 6 furthest away. Your teacher has also laid out four stars in a line perpendicular to the line of the planets.
[00:09:44.45] Your team will use a quadrant to measure the distance from the sun to your assigned planet. Please be as accurate as you can, and measure to the nearest centimeter. Write the planet number and distance on your data sheet.
[00:09:58.30] Now it's time to measure the parallax angle. Take your quadrant and lay the meter stick down in line with the planetary line, so that it points to the sun. Place the middle of the protractor, the 50 centimeter mark on your meter stick, in the center of your planet. Then use the plumb-bob to point to the star you are measuring, and record the angle.
[00:10:20.07] STUDENT: 35.
[00:10:21.27] PROFESSOR BLACK: Be sure to write down the correct angle. It should never be greater than 90 degrees. Write this angle on your data sheet, and then find the angles for the other three stars. Your teacher may have you repeat the process for other planets, so that each planet has been measured by several different teams.
[00:10:59.27] Back in the classroom, you will share your measurement for your planet with the other teams. And they will share theirs with you. Your teacher will write them down on the board.
[00:11:08.11] Now let's do the calculations on the measurements. We'll use the same procedure you used to find the height of your local landmark. Here's an example.
[00:11:17.53] Let's say you're calculating the distance to Star A, as measured from Planet 1, which is 2 meters from the sun. You found the angle to be 60 degrees. Using the formula, you take the tangent of 60, which is about 1.73, and multiply it by 2 meters. And you get 3.46 meters as the distance to Star A.
[00:11:40.14] Now go ahead and do your own calculations for each of your stars from each of the planets. Now find the average distance to the star as taken from each one of the six planets. Once you are done, your teacher will tell you the actual distances from the sun to each one of the stars.
[00:12:17.71] To do an error calculation, take your average distance to that star and subtract it from the distance that your teacher tells you. Then divide that difference by the actual distance to the star and convert it into a percentage. That will tell you how far off you were as a percentage of the actual distance.
[00:12:35.23] Make sure you write all of your calculations down. You should see something pretty interesting. But I'll let you discover that.

[00:13:02.80] Now that you've done the preliminary calculations, you can analyze and compare your results. Looking at the percentage errors as you've calculated them for each of the stars, you should notice a pattern. The stars that are closest to us will be more accurate. You should also notice that the further the planet is away from the sun, the more accurate the estimated distance is.
[00:13:26.21] Why is this? Why is it difficult to measure the distance to a star if the planet is close to the sun or if the star is far away? Turn to your neighbor and discuss ways in which professional astronomers might get more accurate parallax angles.
[00:14:01.60] The reason that it becomes hard to measure a star beyond about 100 light years is that the parallax angle becomes way too narrow, so that the error of measurement just becomes too big compared to the angle we're measuring. Obviously, beyond 100 light years, we either need a better way of measuring the parallax angle, or an entirely new technique of measuring the distance to a star.
[00:14:23.46] One way that you can get a more accurate parallax angle is to get further away from the sun. The further away you are from the sun, the more distance you travel each year and the larger the parallax angle is going to be. Even for nearby stars, the parallax angle is very small.
[00:14:41.57] For example, Alpha Centauri, which is the nearest star system to us, has a parallax angle that's less than 1 arc second. For a star to have a parallax angle of 1 arc second, it would have a distance of 3.26 light years. In fact, that distance, 3.26 light years, is called a parsec, meaning it has a parallax angle of 1 arc second.
[00:15:04.64] If you send a satellite into space to measure the parallax angle, you won't have any interference from the atmosphere. And that parallax measurement will be much more accurate. From 1989 to 1993, they Hipparcos satellite did just that. For 118,000 stars it measured the parallax angle 10 times more accurately than anything that had ever been done from the ground before. For one million stars, it measured the paralyze angle to an accuracy of 25 milli-arc seconds, which is still four times better than anything that had been done from the ground.
[00:15:39.32] We can now extend our distances to the nearby stars out to over 500 light years. Compared to the scale of our Milky Way galaxy, which is 100,000 light years across, 500 light years is still just in our local neighborhood. Astronomers use a scale called the distance ladder with a series of overlapping techniques that allow us to extend beyond 500 light years out to the edge of space. But it all depends on the first rung of the ladder, which is the parallax measurements.
[00:16:09.89] You may want to do some research into these amazing techniques or perhaps do some research on the history of land surveying and solar navigation. If you want to read a thrilling story, research the fate of the HMS Endurance and how Ernest Shackleton, Frank Worsley, and four others rescued their stranded crew mates by a perilous voyage in a small lifeboat, traveling over 1,200 kilometers across storm-wracked ocean to South Georgia Island, using only three sightings of the sun to navigate.
[00:16:41.71] We've talked about just one of the three coordinates for finding the position of a star in three-dimensional space. Perhaps you'd like to learn about the other two and how they are measured, or use some free astronomy software to compare the actual parallax angles of stars with their distances in light years. Finally, you might want to research how 3D movies or images are created, and how your eyes are tricked using polarized filters or using different colored lenses to see separate images.

[00:17:13.12] Your teacher will help you decide which subjects will be good for an extension of this activity. I hope you've enjoyed this lesson today and that you've learned how important parallax and stereoscopic vision are to many areas in science and technology. Until we meet again, this is David Black from Walden School of Liberal Arts. I hope to see you out there.
[00:18:24.21] Finding the position of stars in three-dimensional space is a very important concept in astronomy. We have to be able to find the star's position before we can determine such things as intrinsic brightness, luminosity, absolute magnitude, and so on. Understanding parallax is not only important for astronomy, but also for surveying, mathematics, physics, and many other fields.
[00:18:47.43] This lesson should take about 90 minutes to complete. You may want to lead into the activity and do the introductory segments during one class period, and then do the actual outdoor activity during the next class period, as well as the calculations. The purpose of this lesson is to accomplish the following objectives.
[00:19:05.19] By the end of the lesson, the students will be able to understand and explain the concepts of parallax, parsec, light years, and how they apply to astronomy and finding the distance to stars. They will be able to calculate the distance to simulated nearby stars and the height of local landmarks using the tangent function. They will also be able to apply their knowledge to such fields as surveying and 3D imagery.
[00:19:32.18] To construct this quadrant for doing your measurements, you'll need a length of PVC pipe one meter long or a wooden meter stick. You'll also need a protractor, a length of string or yarn, and then some sort of weight like this one-hole rubber stopper, and then, of course, some tape to put it all together. At the center of your meter stick, attach the protractor like I've done here.
[00:19:56.33] And then tie the string to it so that it hangs from the hole at the very center of the protractor. Make sure that the string is free to swing backward and forward. You'll need enough of these materials to make one quadrant for each group in your class. Each group will also need to have a scientific calculator that can do trig functions, especially the tangent function, or they need to have access to tangent tables.
[00:20:20.71] To do the outside activity, you'll need to have some objects that can serve as simulated planets and stars. You'll need to have six planets and five stars, including our sun. These objects could be rocks. They could be pieces of card stock or poster board that are cut out. They could be painted by your students to look like stars or planets.
[00:20:43.76] You'll also need to have lengths of string or rope that can be stretched out perpendicular to lie out the planets and the stars. Each group will also need to have the two data sheets from the lesson plan on which they can record their measurements and their calculations. The first thing you'll need to do is to lay out two lengths of string or rope so that they're perpendicular to each other. Use one of your quadrants to get as close to 90 degrees as possible.
[00:21:10.58] At the intersection of the two ropes, place our sun, which could be a cardboard cut-out or a rock or other object. From the sun, lay out the planets along the baseline. Make sure that you measure the distance to each planet. You could, for example, lay them out at 1, 2, 5, 7, 10, and 15 meters from the central sun. Along the perpendicular line leading away from the sun lay out your four stars, measuring the distance to each one as accurately as possible.

[00:21:41.28] For the introductory portion of the class, you'll need to find a local landmark and then calculate or research its height. Using a map or Google Earth, find the distance from your school to that local landmark. Of course, you could have your students do this instead. But you might want to have the answers already worked out so that you can save some time.
[00:22:00.94] Once you have your diagram laid out, either on a parking lot or on a practice field, and you've got your local landmark all decided on and measured, you're ready to go. As they progress through the activities, you'll want to help your groups of students work through the calculations, making sure that they're getting the correct measurements. For example, when you're using a protractor, the students will often get incorrect angles because they might forget to subtract from 180. If you see any measurements that are greater than 90 degrees, you know that they've done something wrong.
[00:22:32.78] Once the students have made their measurements and you return to the classroom, what you'll want to do is make sure that each group of students has done their calculations and that they take their measurements and average them together so that they get an average distance from the sun to each star as measured from the different planets. You'll want to record the student averages for the distances to each one of the stars.
[00:22:54.37] Finally, once you have all the measurements to the stars recorded and written up for the students can see them, you'll want to share with them what the actual distances are and have them do an error calculation. Have them take their distance, subtract it from your distance and find the difference, then take that difference and divide it by your measured distance. If you times it by 100%, they'll now have a measurement of how far off they are as a percentage of the actual answer.
[00:23:20.84] As they start looking at the patterns in their data, they should notice that the further planets are away from the sun, the more accurate their answers are likely to be. You should also see that the further away a star is, the less accurate its answer is. Talk to them about how as you get closer and closer to 90 degrees, the tangent function can change dramatically, and so errors of measurement can make your final distance quite inaccurate.
[00:23:45.89] Discuss also that, using parallax measurements from Earth, we can only measure the distance to stars out to about 100 light years. Now that we have space-based observations from the Hipparcos satellite, we can extend the parallax measurement scale all the way out to 500 light years, because now our parallax angles are much more accurate.
[00:24:05.44] I have suggested some extension activities. You can choose which ones you'd like to have your students pursue or perhaps have them choose. They can do additional research. They can write up reports. They can also see how the same technique of doing parallax is used in surveying, in navigation, in 3D imagery, and in many fields of science and technology.
[00:24:26.99] If you'd like to try out some more lessons on stellar astronomy, I'm gradually creating some lesson plans that I'm posting onto my blog site, spacedoutclass.com. I'd also appreciate any comments or suggestions that you could make, so that I can continue to improve these lesson plans.

[00:24:44.08] I hope you enjoyed this lesson. And if you have any questions or comments, feel free to email me. My email is elementsunearthed@gmail.com. I would love to hear back from you on any ways that you are using these lesson plans.
[00:24:59.60] Thank you for teaching this lesson to your class. I hope your students enjoyed it. Until next time, this is David Black. I'll see you out there.