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EXPANDING STUDENT SPATIAL INTUITION TO LARGER SIZE SCALES: A HYBRID HANDS-ON AND COMPUTER VISUALIZATION APPROACH

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Abstract

Most students have an intuitive understanding of how to gauge the distances to objects in their local environment. Through a combination of binocular vision and visual cues such as the perceived sizes of known objects, students can construct a three-dimensional mental model of their local surroundings, and use it to make sense of their environment.
They do not typically understand, however, that the same geometric principles behind binocular vision and depth perception are also used for quantitative distance determination by triangulation and astronomical parallax. We have built a hybrid exercise combining experiential learning with computer visualization for undergraduate students to explore distance determination in the local terrestrial and astronomical contexts in an effort to help them bridge their intuitive understanding to geometries where distance measurement is not possible visually, but is possible via more precise measurements made with instrumentation.
Students explore distance determination in an outdoor setting where the distances to objects (~50m) are too large for intuitive distance measurement, but can be determined quantitatively through a simple triangulation process. By measuring the direction to a target object from two different positions separated by a known distance, they can determine the distance to the target. This triangulation method is used by moving ships at sea, to determine the distance to, say, a visible lighthouse. It is also the method by which astronomers measure the distance to nearby stars (In this case, the "moving ship" is the Earth in its orbit about the Sun.).
The second component of the activity involves using the multi-perspective visualization capability of the WorldWide Telescope (WWT) virtual environment. WWT, originally developed by Microsoft Research, and now managed by the American Astronomical Society, is freely available to the world community. WWT represents real astronomical data in a three-dimensional environment that students can investigate from a variety of physical perspectives. With this software, students can compare the apparent locations of nearby stars from widely separated vantage points (much larger than the size of the Earth's orbit), making the shifts in star positions due to the parallax effect obvious. They can see how their view of universe changes as they change their observing location, connecting their intuitive understanding of distance measurement, and their experience with terrestrial triangulation, to the astronomical realm.
Assessment data indicate that, after participating in this hybrid activity, students better connect their intuitive understanding of distance determination to the quantitative calculations required for precise measurement of distance.

Keywords: *Undergraduate science education, STEM, visualization, laboratory activities*.

1. Introduction

Geometrical and spatial relationships play an important role in many STEM disciplines. From the folding structure of biochemical proteins to the stratigraphy of the Earth's crust to the relative positions of stars in the universe, spatial structure influences the function and evolution of the natural world. Consequently, STEM learners must develop some facility in visualizing, interpreting, and mentally manipulating spatial structures in order to better comprehend the physical processes that drive phenomena in their field-specific environment (Janelle, Hegarty, & Newcombe, 2014). Pedagogy that seeks to develop students' spatial thinking capabilities is likely to improve student understanding of STEM content, not only in the discipline under study, but possibly across disciplines where spatial thinking skills are essential.

The US National Research Council, in its landmark report "Learning to Think Spatially," defines spatial thinking as follows:

> *Spatial thinking is based on a constructive amalgam of three elements: concepts of space, tools of representation, and processes of reasoning. It depends on understanding the meaning of space and using the properties of space as a vehicle for structuring problems, for finding answers, and for expressing solutions. By visualizing relationships within spatial structures, we can perceive, remember, and analyze the static and, via transformations, the dynamic properties of objects and the relationships between objects.* (NRC, 2006)

As learners develop spatial thinking skills, they become adept at interpreting spatial problems, and, moreover, create a formalism for processing new information and discerning new relationships.

One especially important aspect of spatial thinking is "perspective taking," the ability to visualize physical structures from a spatially different perspective (Liben & Downs, 1993). It includes, for example, the ability to visualize one's town or neighborhood from above, and thereby connect information on a map with real streets and buildings. It is essential for the investigation of three dimensional structures, as a single perspective provides only a two-dimensional projection orthogonal to the line of sight. Students can correctly visualize the appearance of a structure from a different physical perspective only if they fully understand its distribution in three dimensions.

Perspective taking is critically important for the study of fields where relevant geometries are not directly accessible by the learner. While it might be possible, for example, to ride in a hot-air balloon above a town to see its structure from a map-like perspective, it is not possible to view all of the layers of the Earth's crust from any perspective, nor is it possible (at least in the near-term) to view our solar system from a perch high above its orbital plane. Yet in these disciplines, structures are often best visualized from these inaccessible perspectives, and textbook authors often adopt these perspectives for explanatory diagrams (Fitzgerald et al., 2011). Thus it is implicitly expected that students possess perspective taking skills as a prerequisite for STEM coursework, and those with limited skill often struggle with course content (Plummer, Bower, & Liben 2016).

2. Computer visualization and the WorldWide Telescope

Visualization software can provide students with views from inaccessible perspectives, and can help students link views of complicated structures from a variety of perspectives. Though not immersive or fully experiential, such software generates visual cues that aid students in the perception of the simulated three dimensional environment. By dynamically shifting their observing perspective, visualization software allows students to "fly though" complex geometries, giving them a more intuitive view of their three dimensional structure. With this type of experience, students can make use of "embodied cognition," a process of using perceptual information to aid in complex mental tasks, such as perspective taking (Wilson, 2002).

The WorldWide Telescope (WWT) is one type of visualization software, specifically designed to display three-dimensional astronomical information in a pseudo-3D immersive environment. Originally developed by Microsoft Research and currently managed by the American Astronomical Society, WWT is freely available for installation on Windows computers, and now also available as a web-based client (see http://worldwidetelescope.org/ for more information). WWT offers free and spatially-oriented access to a worldwide trove of real astronomical data, including the positions and relative velocities of millions of celestial objects, scientific imagery, and results from all-sky surveys (Wong, 2008). In addition to its capability as an interrogative tool for these data, WWT can be programmed to provide scripted and controlled interactions with this simulated universe. These interactions are called "tours," and they provide a rich mechanism for the development of curriculum for learners of astronomy. Importantly for the application discussed in this paper, tours can seamlessly shift a student's observing perspective from one location to another, thereby facilitating the perspective taking required for a fuller understanding of distribution and relative positioning of stars in our local universe.

3. Understanding astronomical parallax: A laboratory exercise

One of astronomy's most fundamental measurements is also one of its most difficult. Ascertaining the distance to even the most nearby stars beguiled astronomers for centuries, mainly because, as simple points of light, they offer no visual cues regarding their distance. Moreover, our single Earthbound perspective limits our ability to use triangulation techniques to estimate a distance. Lastly, and perhaps most importantly, all stars, even the most nearby, are incredibly far away compared to any terrestrial size scales. These distances were ultimately determined the method of astronomical parallax, a technique that makes use of the Earth's orbit around the Sun to obtain observations of the apparent positions of stars from different observing positions. The shift in a star's apparent position over the course of a six months (one-half an Earth orbit) is called the parallax shift, and it is inversely proportional to the star's distance. Because of the relatively small size of the Earth's orbit compared to the incredibly large distances to even nearby stars, this shift is incredibly small and cannot be detected via naked eye observations. Even with telescopes , this measurement is difficult, and it was first accomplished only in 1838, some 200 years after the invented of the astronomical telescope (Bessel, 1838).

The method of astronomical parallax is the fundamental building block for the cartography of the universe, and an understanding of this concept is essential for further student learning in astronomy. It is also an inherently geometric problem requiring perspective taking skills, as it depends on how views of stars differ when observed from spatially separated observing locations. To build student understanding of this concept, and additionally to foster student perspective taking skills, we have developed the curriculum for a laboratory activity focusing on astronomical parallax.

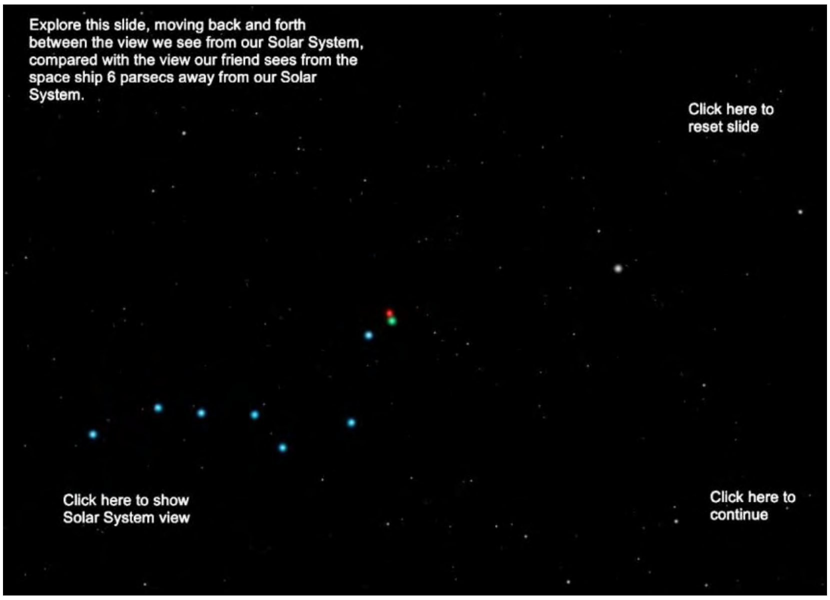
This laboratory activity is designed for a three-hour standalone period as part of a sequence of laboratory activities for an introductory astronomy course catering to non-science undergraduate students. It is built in a hybrid format, with a experiential, hands-on component focusing on the measurement of parallax in a terrestrial environment (sometimes called "triangulation"), and a WWT-based component designed to help students transfer their Earth-based intuition to astronomical environment (see http://wwtambassadors.org/bucknell-wwt-parallax-lab for more details and access to downloadable materials).

The hands-on component of the laboratory activity involves measurement of the parallax shifts for prominent objects in the outdoor environment. Here, the distances to objects are much smaller, and students can see directly how these objects appear to shift position (relative to the distant background) as the students move from one observing location to another. To mimic the astronomical geometry, measurements of the angular separation between the reference direction and the direction to the nearby object are made at several positions in an "orbit" around a central "Sun." The Sun is a pizza tin marked with twelve sections denoting the months of the year. Students use a surveyor's transit to identify the lines of sight to distant and nearby objects, and to determine the parallax shift of the nearby object. Based no the measured parallax shift, and the size of the circular "orbit" (four meters in this terrestrial case), they can then calculate the distance of the nearby object. The method is directly analogous to the astronomical case; however, in this terrestrial environment, students can profitably apply their Earth-based intuition to interrogate the geometry, and even more importantly, they can access this geometry experientially by walking around the open field.

Figure 1. Setup for terrestrial parallax measurements. Students lay out a circular "orbit" from which to make measurements (left). Using a surveyoor's transit, they measure the angular separation between a nearby object and an object in the distant background (right).

In the second component of the laboratory activity, students use WWT to transfer their parallax intuition from the terrestrial to the celestial environment. Using the pseudo-3D multi-perspective capability of WWT, students view the well-known asterism the Big Dipper from Earth, and from another location far from Earth. Though this second viewpoint is not physically accessible, the software can provide a simulated view from this location. Over the large baseline between these locations, the parallax shift is quite obvious (as it is in the terrestrial case), and students can easily discriminate between nearby and faraway stars. They make detailed measurements of the parallax shift, and determine the distances to several Big Dipper stars.

Figure 2. A WWT screenshot depicting the distances to the stars in the Big Dipper, viewed from a position very far from Earth. Note the apparent distortion of this common asterism.



4. Assessment

This laboratory activity was piloted in an astronomy course in a small, predominantly undergraduate university in the northeastern United States over three consecutive years. Students participated in both pre- and post-instruction assessment activities consisting of a multiple-choice diagnostic text (Nottis et al., 2015), and post-instruction quizzes and exams. Our data suggest that after instruction, our students are better able to use their perspective taking skills to connect views of the parallax geometry from a variety of observing perspectives, including the detached, "overhead" view often presented in textbook discussions of this phenomenon. Students also appear to be able to correct apply geometrical principles to calculate the distance to an object, given inputs of parallax shift and the separation between observing locations.

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