BUILDING A THREE DIMENSIONAL UNIVERSE FROM THE CLASSROOM: MULTIPERSPECTIVE VISUALIZATION FOR NON-SCIENCE UNDERGRADUATES

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Abstract

We develop three-dimensional mental models of our physical environs from two dimensional imagery we collect with our eyes. This is possible only because we move through that environment, viewing it from multiple perspectives, and construct a model consistent with a collection of two-dimensional views. The technique works well for structures whose sizes are comparable to the magnitude of our movements, such as rooms, buildings, and even cities; but for much larger structures, we are effectively limited to a single perspective, and therefore must create mental models from indirect measures.

The astronomical realm is almost always in this latter category, and student understanding of the structure of the universe is limited by their inability to use multi-perspective techniques to generate an accurate mental image of astronomical structure. Without an accurate model, students tend to underestimate the distances to and between astronomical objects, leading to inaccurate assumptions regarding the overall size of the universe, the interactions between celestial objects, and our location within and among these structures.

To improve student understanding of the size, scale, and structure of our universe, we have developed hybrid laboratory activities based on a mix of hands-on discovery with physical models and multi-perspective visualization using the WorldWide Telescope (WWT) virtual environment. WWT, developed by Microsoft Research, managed and supported by the American Astronomical Society, and freely available to the world community, represents real astronomical data in a three-dimensional environment that students can investigate from a variety of physical perspectives. They can virtually “fly through” astronomical structures and thus use the same techniques they use in their local everyday environment to develop an accurate mental model on an astronomical scale.

These new lab activities connect indirect measurements of distance and structure (based on real astronomical data) to visualizations of those same structures, so that students understand the techniques by which structure is measured, and create accurate mental models of those structures. This not only improves their understanding of their astronomical environs, but also improves their understanding of the physical processes that occur in our universe.

We will present examples of these activities, and assessment data measuring the improvement in student understanding of astronomical size, scale, and structure, as a result of their interactions with these materials.

Keywords: *undergraduate science education, STEM, visualization, laboratory activities*

1. Introduction

Three dimensional spatial visualization and reasoning are crucial for success both in the academic environment (Titus and Horsman 2009) and in careers in engineering, physical sciences, and the arts (Humphreys, Lubinski, and Yai 1993), yet many students struggle with manipulations and interpretations of three-dimensional objects (Sutton, Heathcote, and Bore 2007). The visualization process involves many steps, ranging from visual perception of an object, to the creation of a mental image of that object, and the imagined manipulation of that object in three dimensions (Mathewson 1999).

In astronomy, spatial visualization skills are absolutely essential, and study in this subject offers many opportunities to practice and hone these skills. Our universe is inherently three dimensional, but most astronomical measurements access directly only two spatial dimensions. From our single vantage point, astronomers must infer the third dimension (distance) from interpretations of observational data. We never “see" the three dimensional universe directly, but instead construct and visualize a geometrical model of it based on indirect evidence. It's perhaps not surprising then that students of astronomy have great difficulty constructing an accurate internal model for the universe and its contents. They are particularly challenged with issues of scale. Several studies have shown that very often they underestimate the distances to astronomical objects such as the Sun and the next nearest star (Sadler 1992; Trumper 2001). In a recent study, Miller and Brewer (2010) find that the median response for the distance to the Sun is about a factor of three smaller than the real value, and the median response for the distance to the nearest star is smaller than the real value by a factor of 250,000.

There are numerous reasons why many scientific concepts are challenging for learners. Some concepts encompass multi-level content: the “macro" level or that which can actually be observed, the “submicro" or particulate level, and a “representational" or symbolic/mathematical level (Johnstone, 1993). While experts can simultaneously work at all levels, skillfully shifting between them, novices are unable to do so. They have difficulty knowing where to focus their attention and as such, have a problem distinguishing “signal" from “noise" (Johnstone, 1991). This can result in partial or incorrect understandings of concepts. Since many scientific concepts are unobservable and cannot be understood through direct experimentation, students must deal with the non-visible as well as the concrete levels (Thiele and Treagust, 1995). “Non-observable entities” (Byrnes, 2001, p. 261) have been identified as a key reason why students might hold what have been labeled misconceptions.

2. Hybrid Hands-on and Virtual Environment Laboratory Activities

To respond to this challenge in undergraduate astronomy teaching, we have developed a series of hybrid laboratory activities that combine a hands-on exploratory component with computer-aided visualization component. Students can vastly improve their three dimensional spatial reasoning skills with practice manipulating three-dimensional objects, particularly when changes in perspective are involved (see e.g., Duesbury and O’Neil 1996), so we re-create astronomical geometries in the form of models that can be interrogated on human scales. So, for example, students investigate the geometry of our Milky Way’s galactic disk with CDs and pizza pie tins, contemplate the expansion of the universe with a stretching spring, and gain a perspective on astronomical parallax by measuring the distances to lampposts on campus. Because students can move around the objects of study, they develop more durable mental models of the geometries they encounter.

It is difficult, however, to transfer this geometric understanding to the astronomical realm, largely because of the tremendous change in scale, as well as our inability to interrogate the astronomical geometries from multiple perspectives. Multiperspective visualization software, such as the WorldWide Telescope (WWT), can overcome these problems in a virtual environment. WWT is a visualization environment that enables a computer to function as more than a virtual telescope; it combines archival data from the world’s best ground-and space-based telescopes into a three dimensional universe that can be viewed not only from an Earthbound perspective, but from any other perspective in the universe. Within this environment, students can “fly though” an astronomically-accurate universe in the same way they move around and through the human-scale model environments they encounter earlier in each laboratory activity.

WWT was recognized in the 2010 U.S. National Academy of Science Decadal Survey of Astronomy (Blandford, 2010) as “a significant contribution to the public understanding of Astronomy,” calling it “a corporate version of previously under-funded efforts of astronomers to accomplish similar ends, [that] coordinates the world’s public-domain cosmic imagery into one resource, allowing people on home PCs to explore the cosmos as if they were at the helm of the finest ground and space-based telescopes.” WWT is an ideal platform for widely-usable and engaging labs because it is a free resource available to any school or any member of the public, with the potential to reach an ever-broadening and diverse audience, including populations that are traditionally underserved in STEM education. WWT was originally a free Windows-only program which has now expanded to include an HTML5 (web-based, platform-independent) version. Today, the user base of WWT is in the tens of millions, and all versions of the software are freely accessed at worldwidetelesope.org.

In partnership with WWT (now administered and supported by the American Astronomical Society), we have developed three hybrid hands-on and virtual laboratory activities for the undergraduate introductory astronomy classroom. For many non-science students, a general education astronomy course may be their only opportunity to develop spatial reasoning skills, even though these skills have been shown to be useful in both science-based and non-science careers (Uttal, Miller, and Newcombe 2013, Humphreys, Lubinski, and Yai 1993). Below we detail one example activity.

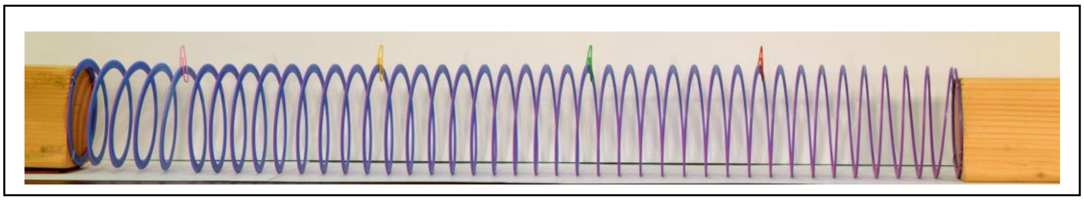
3. An Example: Modeling the Large-scale Structure of the Universe

The structure of our universe on the very largest scales – that of galaxies and the large distances between them – can be understood as one of AUTHOR'S "non-observable entities." Only a handful of galaxies can be seen with the naked eye, and even for those objects, no direct observation can show that they are many orders of magnitude farther from Earth than the stars that appear beside them in the night sky. Distance determination on this size scale is entirely based on inference, using non-intuitive relationships based on chains of scientific observation and reasoning. Perhaps the most successful of these relationships involves levering the homologous expansion of the universe, and the concomitant linear relationship between recession velocity and distance, to determine the distances to individual galaxies and reveal their large-scale distribution in our universe. This relationship is called the Hubble Law, and it is the primary tool with which astronomers chart the universe.

We have developed a hybrid hands-on and virtual laboratory activity designed to help students address the large scale structure of the universe, and construct a model of this universe that allows them to draw accurate conclusions regarding the physical processes that occur on this scale. In both the hands-on and virtual components of the activity, we ask students to investigate the geometry from both an *in-situ* (i.e., Earthbound) perspective, and from a detached, or "bird's-eye," view, with emphasis on how the structure revealed more clearly in the detached view can be inferred from measurements made from the *in-situ* perspective.

To build an understanding of the large-scale structure of the universe, students must first grapple with one non-intuitive concept – the Hubble Law relationship – before they can use it as a tool for their cosmic cartography. This relationship is an inextricable consequence of a homologous expansion, and so students first investigate this effect in a non-astronomical and more intuitive tabletop environment with a "Slinky" spring and paper clips. The spring represents an entire universe, while the paper clips attached to individual coils on the spring represent galaxies in that universe. By taking measurements of the distances between "galaxies" with the spring stretched to various lengths, students construct the velocity-distance Hubble relationship, and determine that it holds for all observers, regardless of which galaxy they inhabit. The universality of this relationship reinforces the idea that large-scale galaxy motions are a consequence of a single process – the expansion of the universe – which they can clearly see from the detached perspective as they stand over their "universe."

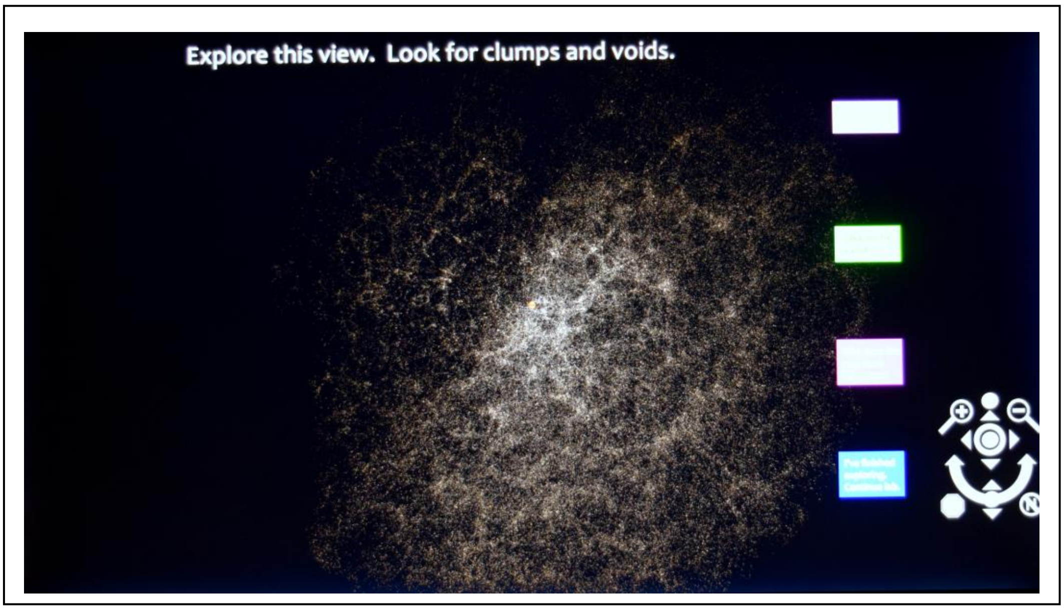
Figure 1. The tabletop expanding universe used by students to construct and explore the Hubble Law relationship Note the colored paper clip "galaxies" attached to several coils on the spring.



The idea that galaxies are merely particles trapped in the flow of a universal expansion is key to the students' subsequent attempts to map the spatial distribution of these objects. By inverting the Hubble relationship, they can determine the distances to galaxies using measurements of their recession velocities – measurements that can be obtained from our *in-situ*, Earthbound perspective. Students perform these measurements on real astronomical data, using WWT's data retrieval capability, and build, from the concepts introduced previously in this activity, *their own* three-dimensional map of a small piece of the universe.

WWT then allows them to interrogate their construct visually. They can leave their Earthbound perspective and "fly though" their universe to see the distribution of galaxies in three-dimensional space. The two dimensional celestial sphere is shattered, and replaced with a rich space of depth. With the addition of data from large astronomical surveys (most notably the Sloan Digital Sky Survey; Abazajian et al. 2009), students see the structure of the extragalactic universe from multiple in-situ perspectives, and perhaps most importantly, from a detached perspective as well. It's from this last perspective that the fundamental character of the distribution of galaxies is most apparent. The frothy, cobweb-like structure delineated by the galaxies informs the physical processes that take place on the universe's largest scales – the potential for interactions between galaxies, and the competition between gravity and the expansion of the universe as manifested in galaxy clustering and the overall inhomogeneity of the distribution. Indeed, even the history of the universe is encoded in its current structure, as well as clues for its subsequent evolution.

Figure 2. WWT display of the galaxies in the Sloan Digital Sky Survey Each white dot in this display corresponds to an individual galaxy. The frothy spatial distribution of galaxies is observed from an external perspective some one billion light years from Earth. Earth's position is signified by the large dot at the center of the view.



3.1 Implementation and Initial Assessment

The laboratory activity described above was implemented in a small liberal arts college environment in two instances: in beta test mode to a small (N=10) group of volunteer undergraduate students in the summer of 2015, and in a larger (N=37) laboratory classroom associated with a fall semester introductory astronomy course designed for non-science undergraduate students. In this paper, we report on the student response to the summer beta testing; a report on the fall 2015 administration is forthcoming.

Students completed the hybrid lab activity and associated diagnostic follow-up in a single three hour period in July 2015. The primary purpose was to test the procedures with real students, and to identify process and content issues that produced misinterpretation or confusion. Students were observed by a trained laboratory instructor as they performed the lab activities, and interacted with this instructor throughout the activity. At the conclusion of the lab, students completed a four-question "Lab Quiz" designed to test their understanding of the lab content, and a seven-question "Feedback Form" designed to gauge their engagement in the lab, interest in the presented material, and satisfaction with the lab activity.

Based on the expert observation and the students' responses to the Lab Quiz, we conclude that students were able to articulate the purpose of the lab very well; for example, they were all able to describe the Hubble Law as a consequence of the expansion of the universe. Nine of ten students could explain why all distant galaxies appears to be moving away from Earth, and seven of ten correctly described the spatial distribution of galaxies in the local universe.

Student affective responses also indicated a high level of engagement and interest in the lab activity. Most found the experience enjoyable, and commented on the activities as "interesting" and "informative." When asked which part of the lab activity they found most helpful for their understanding, the group split nearly in two, with nearly half identifying the WWT multimedia interaction, and the other half noting the hands-on activity with the Slinky spring.

4. Summary and Conclusions

We have developed several hybrid hands-on and virtual laboratory activities designed to help students address the concepts of size, scale, and structure in the astronomical environment. Initial results suggest that students find the hybrid approach engaging and helpful in their efforts to build an understanding of astronomical size, scale, and structure. Further research is necessary to determine whether persistent improvement in student understanding is obtained with these methods, and whether these activities lead to an improvement in more general spatial reasoning skills.

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