Title
Dynamic Visualizations As Tools For Supporting Cosmological Literacy

Author
Buck, Zoe Elizabeth

Publication Date
2014

Peer reviewed|Thesis/dissertation

UNIVERSITY OF CALIFORNIA

SANTA CRUZ

DYNAMIC VISUALIZATIONS AS TOOLS FOR SUPPORTING COSMOLOGICAL LITERACY

Dissertation submitted in partial satisfaction
of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

EDUCATION

By

Zoë Elizabeth Buck

June 2014

The dissertation of Zoë Buck is approved:

____
Professor Doris Ash

____
Professor Jerome Shaw

____
Professor Joel Primack

____
Professor Eduardo Mosqueda

____
Tyrus Miller
Vice Provost and Dean of Graduate Studies

TABLE OF CONTENTS

Figures

DYNAMIC VISUALIZATIONS AS TOOLS FOR SUPPORTING COSMOLOGICAL LITERACY

Dissertation Abstract

Zoë Elizabeth Buck

My dissertation research is designed to improve access to STEM content through the development of cosmology visualizations that support all learners as they engage in cosmological sense-making. To better understand how to design visualizations that work toward breaking cycles of power and access in the sciences, I orient my work to following "meta-question": *How might educators use visualizations to support diverse ways of knowing and learning in order to expand access to cosmology, and to science?* In this dissertation, I address this meta-question from a pragmatic epistemological perspective, through a sociocultural lens, following three lines of inquiry: experimental methods (Creswell, 2003) with a focus on basic visualization design, activity analysis (Wells, 1996; Ash, 2001; Rahm, 2012) with a focus on culturally and linguistically diverse learners, and case study (Creswell, 2000) with a focus on expansive learning at a planetarium (Engeström, 2001; Ash, 2014).

My research questions are as follows, each of which corresponds to a self-contained course of inquiry with its own design, data, analysis and results:

1) Can mediational cues like color affect the way learners interpret the content in a cosmology visualization?
2) How do cosmology visualizations support cosmological sense-making for diverse students?

3) What are the shared objects of dynamic networks of activity around visualization production and use in a large, urban planetarium and how do they affect learning?

The result is a mixed-methods design (Sweetman, Badiee & Creswell, 2010) where both qualitative and quantitative data are used when appropriate to address my research goals. In the introduction I begin by establishing a theoretical framework for understanding visualizations within cultural historical activity theory (CHAT) and situating the chapters that follow within that framework. I also introduce the concept of *cosmological literacy*, which I define as the set of conceptual, semiotic and cognitive resources required to understand the scientific Universe on a cosmological scale. In the first chapter I use quantitative methods to investigate how 122 post-secondary learners relied on mediational cues like color to interpret dark matter in a cosmology visualization. My results show that color can have a profound effect on the way that audiences interpret a dynamic cosmology visualization, suggesting a closer look at learning activity. Thus in the second chapter I look at how the visualizations are used by small groups of community college students to make sense of cosmology visualizations. I present evidence that when we look past linguistic fluency, visualizations can scaffold *cosmological sense-making*, which I define as engaging in object-oriented learning activity mediated by concepts and practices associated with cosmological literacy. In the third chapter I present a case study of an urban planetarium trying to define its goals at a time of transition, during and after the development of a visualization-based planetarium show. My analysis reveals several historical contradictions that appear to impel a shift toward affective goals within the institution, and driving the implementation of visualizations, particularly in the context of immersive[1] planetarium shows. I problematize this result by repositioning the shift toward affective goals in the context of equity and diversity. Finally in my conclusion I present broad recommendations for visualization design and implementation based on my findings.

[1] Immersive visualizations and shows refer to three-dimensional images that appear to surround the audience.

Acknowledgments

I would like to acknowledge the efforts, advice and support (both academic and emotional) of the following amazing people: Doris Ash, Joel Primack, Eduardo Mosqueda, Jerome Shaw, Edward Lyon, Linnea Beckett, Alisun Thompson, Mark SubbaRao, Nina McCurdy, Karina Buck, Craig Buck, Yuri Buck Bracey, Christopher Buck Bracey, and my students at Hartnell Community College. This dissertation would not have been possible without them, and without the financial and institutional support of the UCSC Department of Education, Adler Planetarium's Space Visualization Lab, UC-HiPACC and UC-ACCORD.

Introduction: Cosmology, Visualizations and Research Overview

In the introduction to my dissertation I justify my choice to focus on cosmology visualizations by arguing for the importance of developing a cosmologically literate citizenry, pointing out the increasing reliance of cosmology educators on dynamic visualizations, and highlighting the lack of literature on either topic. In doing so, I introduce and define the "dynamic visualization" and the construct of "cosmological literacy." I then critically examine traditional theoretical perspectives for understanding cosmology learning and dynamic visualizations, and introduce cultural-historical activity theory as a more nuanced and productive theoretical tool. Finally, I provide an overview of my dissertation design, going through each chapter in turn to tie together their diverse methodologies within a single mixed-methods research design.

Cosmology as fundamental science content

Developing a "scientifically literate" citizenry has moved to the top of political and educational agendas over the past decades (American Association for the Advancement of Science [AAAS] Project 2061, 1993; Obama, 2014), driving an interest in research on how to develop scientific literacy through effective teaching of fundamental science content. Cosmology is fundamental science content; it is the study of the structure, organization and dynamics of the observable universe. According to the American Association for the Advancement of Science (AAAS), "finding our place in the cosmic scheme of things and how we got here is a task for the ages – past, present, and future... If being educated means having an informed sense of time and place, then it is essential for a person to be familiar with the scientific aspects of the [U]niverse and know something of its origin and structure" (AAAS Project 2061, 1993).

Until 1997, cosmology was regarded as a very uncertain field of astronomy, plagued by persistent theoretical inconsistencies[2] that made it "extraordinarily

[2] One of these inconsistencies was the existence of stars seemingly older than the universe. In 1997-98 the Hipparcos satellite determined that the distance to many old stars had been underestimated. This meant that the old stars were brighter and therefore younger than previously thought, approximately 12-13 billion years old. The discovery of the accelerating

difficult for physicists to take seriously any theory of the Universe" (Weinberg, 1993, p 131). But in the past decade, results from experiments like the Wilkinson Microwave Anisotropy Probe (WMAP) and the Sloan Digital Sky Survey (SDSS) have lent support to a standard cosmology known as Lambda Cold Dark Matter (ΛCDM). ΛCDM is now widely recognized as serious scientific theory, elevating the status of cosmology content in the eyes of the scientific community. Today, being familiar with cosmology content such as the Big Bang is recognized as a fundamental part of scientific literacy (NGSS Lead States, 2013), with the potential to ``convey the preciousness of the cosmic experiment on planet Earth...[and] reveal solutions to the problems that confront us personally and globally" (Primack & Abrams, 2006).

Yet national and state standards have continued to de-emphasize large scale cosmology–whereas in 2006 over 45 states included Earth's orbit and seasons, the phases of the moon, and the eight classical planets in their curriculum standards, fewer than 20 states included the structure of anything outside of the Solar System (Palen & Procter, 2006). The Next Generation Science Standards (NGSS), which were developed by a consortium of 26 states[3] and are likely to be adopted by many

---

expansion of our universe put the time passed since the Big bang at approximately 14 billion years, resolving the old star inconsistency.

[3] These states are: Arizona, Arkansas, California, Delaware, Georgia, Illinois, Iowa, Kansas, Kentucky, Maine, Maryland, Massachusetts, Michigan, Minnesota, Montana, New Jersey, New

states over the next several years, include knowledge of the force of gravity in determining the structure of the Universe, the existence of many galaxies beyond our own, and evidence for the Big Bang, but only for middle school and high school students who have chosen to take astronomy courses (NGSS Lead States, 2013). It is not surprising then that the few studies on cosmology learning have found that participants struggle to conceptualize and articulate what lies outside our solar system (Raphling & Keane-Timberlake 1997; Prather et al. 2002; Schoemer 1999; Sadler 1992). As the nation looks to expand science literacy, states prepare to adopt the NGSS, and educators turn to new technologies to introduce science content, we need to know more about how learners make sense of our Universe across relevant learning environments, and how we can support the development of cosmological literacy in order to expand access to science for all students.

York, North Carolina, Ohio, Oregon, Rhode Island, South Dakota, Tennessee, Vermont, Washington, and West Virginia. Over 40 states have shown interest in the standards. However at the time this dissertation is being written, only six states have adopted the standards: California, Kansas, Kentucky, Maryland, Rhode Island, and Vermont. (Wikipedia, 2014)

Defining cosmological literacy

I define cosmological literacy as the set of conceptual and semiotic resources required to understand the scientific Universe on a cosmological scale. This includes descriptive[4] knowledge of the forces, bodies and systems involved in basic cosmology, and the ability to apply this knowledge appropriately. I use the term literacy in a purposeful way: 1) to invoke the popular phrase of "scientific literacy;" 2) to establish a distinction between proficiency in descriptive cosmology, and numeracy (Steen, 2001), which is also an integral part of cosmology; and 3) to suggest a connection to the Freirian definition of literacy as "a creative act that involves the critical comprehension of reality" (Freire & Macedo, 1987, p 156).[5]

Cosmological literacy can be divided into four facets: systems, forces, observability and scale. *Systems* refers specifically to the components and

---

[4] I use the qualifier "descriptive" here to indicate that I am not referring to a mathematical or numerical understanding of the physics of cosmology, but rather a more qualitative understanding of the basic structure, scale, and properties of the Universe as we know it.

[5] As such, I hope that cosmological literacy, like reading and writing literacy, can be "a vehicle by which the oppressed are equipped with the necessary tools to reappropriate their history, culture, and language practices" (156), by giving learners the tools to interpret scientific cosmology critically in relation to their own cosmologies, and providing access to scientific institutions embedded in systems of power and privilege.

organization of the Universe, *forces* to the role of gravity and the dynamics of gravitational systems, *observability* to the limitation of our current technology and the relationship of what is visible to what is invisible, and *scale* to deep time/space. These facets were used to bound my literature search, to choose appropriate cosmology visualizations, and in the construction of my framework for defining practices associated with cosmological literacy.[6]

Systems: Cosmology includes knowledge of various celestial bodies and systems, including how they are organized, and some of their properties. Our Universe can be organized into systems of increasing scale, bounded by gravity on local scales (planetary systems, star systems, galaxies, galaxy clusters), and at the largest scales, anisotropy after the Big Bang.[7] The largest systems that are gravitationally bound are clusters of galaxies. On very large scales, superclusters of galaxies surround cosmic voids. Regions bound together by gravity have stopped

---

[6] These four themes are based on the goals as dictated by planetarium educators (Small & Plummer, 2010) and national science education standards (NSF, 1996; NGSS Lead States, 2013). They were developed in consultation with cosmology visualizer Nina McCurdy and cosmologist Joel Primack, and modified to align with the content of the Next Generation Science Standards (NGSS).

[7] Anisotropy is the property of being directionally dependent, and can be thought of roughly as the "clumpiness" of material in the early Universe, as opposed to a smooth, uniform distribution.

expanding, but the superclusters are not bound by gravity, and they are expanding faster and faster. In the NGSS, this facet aligns with the cross-cutting concept *Systems and system models*, described as follows: "Defining the system under study—specifying its boundaries and making explicit a model of that system—provides tools for understanding and testing ideas that are applicable throughout science and engineering."

Forces:[8] Cosmological literacy includes knowledge of how celestial bodies and systems interact with each other through gravity, and an appreciation for how this interaction dictates much of the structure of the Universe. In the NGSS, this facet aligns with the following standard for middle school students: *Develop and use a model to describe the role of gravity in the motions within galaxies and the solar system*[9] (NGSS Lead States, 2013). All matter in the Universe, visible and invisible,

---

[8] While gravity is the most pertinent force for basic descriptive cosmology, it is not the only important force in the Universe. Electromagnetic radiation shapes the formation and evolution of stars, among other things, and the Weak and Strong forces are key to understanding the moments after the Big Bang, and the matter that makes up the Universe.

[9] From the NGSS: [Clarification Statement: Emphasis for the model is on gravity as the force that holds together the solar system and Milky Way galaxy and controls orbital motions within them. Examples of models can be physical (such as the analogy of distance along a football field or computer visualizations of elliptical orbits) or conceptual (such as mathematical proportions

interacts through gravity, as does radiation such as visible light. The research on how students think about gravity has revealed that their ideas are heavily based on context (Palmer, 2011). In other words, while most students can talk about gravity and predict its effects on the things they see every day, they do not transfer this knowledge to cosmological systems consistently (Smith & Peacock, 1992; Sneider & Ohadi, 1998; Bar et al., 1994; Nussbaum & Novak, 1976; Nussbaum, 1979; Sneider & Pulos, 1983). Many students link gravity with air (Berg & Brouwer, 1991; Borun & Massey, 1993; Ruggiero et al., 1985; Reynoso et al., 1993; Bar et al., 2007). Thus this facet of cosmological literacy requires knowledge of gravity in the context of cosmology, and an explicit understanding of how interactions on a local scale (e.g. gravity between two celestial objects) can create large-scale patterns that act in non-intuitive ways. This aligns with the NGSS cross-cutting concept *Patterns*, described as "Observed patterns of forms and events guide organization and classification, and they prompt questions about relationships and the factors that influence them" (NGSS Lead States, 2013).

---

relative to the size of familiar objects such as students' school or state).] [*Assessment Boundary: Assessment does not include Kepler's Laws of orbital motion or the apparent retrograde motion of the planets as viewed from Earth.*]

Observability: Descriptive cosmology includes knowledge of some of the limitations of our observations, including what little we know about the invisible components of the Universe. These components include dark matter, dark energy, and their relationship to the Big Bang. Most of the Universe is made of dark matter. Large dark matter "halos" permeate and surround all galaxies, and hold them together gravitationally. Even though cosmologists can't see dark matter, they can measure it by the effects of its gravity. It might be detected directly in underground experiments, through NASA's Fermi Gamma Ray Space Telescope or other instruments, or created at the Large Hadron Collider in Geneva. Einstein's theory of gravity (general relativity) allows space to repel space via dark energy, which is now making the universe expand increasingly rapidly. The invisible Universe is tied to the visible through gravity, and the repulsive effects of dark energy. Although dark energy and dark matter are not mentioned in the NGSS, this facet of cosmological literacy is closely tied to the nature of science (NoS), emphasized in the NGSS, and the fundamental scientific tenet of uncertainty (Buck, Lee & Flores, 2014). According to supplementary NGSS documents: "Indeed, the only consistent characteristic of scientific knowledge across the disciplines is that scientific knowledge itself is open to revision in light of new evidence. " In addition, this facet requires an understanding of the visible Universe, including radiation such as the cosmic microwave background, heat left over from the early Universe. Because of the limitations of deep space, radiation is the primary tool used by astronomers, and analysis of radiation such as spectra can tell us a lot about the Universe. This aligns with the NGSS standard for high school students: *Construct an explanation of the Big Bang theory based on astronomical evidence of light spectra, motion of distant galaxies, and composition of matter in the universe.* [10]

Scale: Cosmological literacy requires an understanding not just of the various systems and how they are organized, but of the scale of these systems, and how that effects them and their interactions. For example, the effect of dark energy versus gravity changes on large scales: whereas gravity dominates on the scales with which we are familiar, dark energy dominates on the scale of superclusters. For experts, understanding of deep time and or space is associated with mathematical practices such as logarithmic scales, and metacognitive practices such as compartmentalizing various cosmic systems, but for learners who are treating the Universe qualitatively, scale through time and space can be very difficult to conceptualize (Tretter, Jones, Andre, Negishi & Minogue, 2006; Dodick and Orion, 2003). This facet of

[10] From NGSS: [Clarification Statement: Emphasis is on the astronomical evidence of the red shift of light from galaxies as an indication that the universe is currently expanding, the cosmic microwave background as the remnant radiation from the Big Bang, and the observed composition of ordinary matter of the universe, primarily found in stars and interstellar gases (from the spectra of electromagnetic radiation from stars), which matches that predicted by the Big Bang theory (3/4 hydrogen and 1/4 helium).]

cosmological literacy is aligned with the NGSS cross-cutting concept of *Scale, proportion, and quantity*, described as follows: "In considering phenomena, it is critical to recognize what is relevant at different measures of size, time, and energy and to recognize how changes in scale, proportion, or quantity affect a system's structure or performance."

These facets incorporate a number of fundamental cosmological concepts and categories, and are inextricable from one another. For example, gravity is responsible for the organization of the Universe, is an important link between the behavior of invisible matter and visible matter, and its impact is highly dependent on the scale of the system. Tremendous progress has occurred recently in the scientific community toward understanding cosmology, including our first picture of the size, evolution, and structure of the entire visible universe that is supported in detail by a wide diversity of observational data (Abrams & Primack, 2011). In the past decade, cosmology has come of age, the standards are finally beginning to catch up, and it is time to build a research base on cosmology learning and teaching, starting with accessible, well-designed learning tools, like dynamic visualizations.

Visualizations as learning tools for presenting complex cosmology content

Much of cosmological literacy is very difficult to conceptualize visually: dark energy, dark matter, gravitational interactions, and systems organized on scales far too large to be viewed through a telescope's eyepiece. Well-designed scientific visualizations could help learners organize these complex concepts externally, supporting them as they construct their own understanding. Scientific visualizations are representations of 3-D+ phenomena, simplified illustrations of complex real life systems, sometimes animated dynamically over time or through space. In cosmology, this often means the rendering of enormous data sets, either collected from cosmological surveys, or simulated using observed cosmological parameters. According to Friedman (2008):

> [The] main goal of data visualization is to communicate information clearly and effectively through graphical means. It doesn't mean that data visualization needs to look boring to be functional or extremely sophisticated to look beautiful. To convey ideas effectively, both aesthetic form and functionality need to go hand in hand, providing insights into a rather sparse and complex data set by communicating its key-aspects in a more intuitive way.

Thus while cosmology visualization is a functional medium for scientists as they work to understand the Universe, it also has the potential to be visually stunning, drawing in learners and showing them real-life phenomena they might never have been able to imagine (Peña and Quilez, 2001). Visualizations are can be learning tools for presenting complex and rigorous cosmology content, without high linguistic demand (Hegarty, Kriz & Cate, 2003). They are a flexible medium that can bring the vast, invisible aspects of the Universe into students' experience, and inculcate students into some of the tools of science.

Over the past decade, modern software has made extending productions to 3D theaters, flat screens, and the Internet comparatively easy (HiPACC website, 2014).

As a result, real scientific visualizations have become one of the most utilized media for presenting astronomy content in both informal settings and classrooms (Yair, Mintz, & Litvak, 2001). This means that we need to know more about how we can use visualizations to support learners as they coordinate multiple ways of conceptualizing, knowing, and representing the Universe.

Visualizations can take advantage of "the power of alternative formats in communicating ideas" (Lee & Fradd, 1998, p 17). Multi-media simulations and visualizations have been shown to support science achievement in biology (e.g. Kiboss, Ndirangu & Wekesa, 2004) and chemistry (e.g. Ardac & Akaygun, 2004), so there is precedent to suppose that they might be used to support learning in cosmology. We also know that such simulations and visualizations can serve to help students generate their own mental images, and deepen their engagement in conversations around the content (Wu, Krajcik, & Soloway, 2001; Hegarty, Kriz & Cate, 2003). Yet we know almost nothing about how learners, especially those from demographics who are typically underrepresented in science, are interpreting and interacting with visualizations. These visualizations are made by scientists, and then disseminated to the media and to learning institutions without being rigorously studied with learners.

Cosmology visualizations are becoming increasingly popular in TV shows like *The Universe* and *NOVA*. They have revolutionized planetariums, expanding potential explorations from the night sky to the entire Universe. And they are becoming more popular in the K-12 classroom (Yair, Mintz, & Litvak, 2001). Thus potential audiences for cosmology visualizations range in age from toddlers to grandparents, in education level from no schooling to professional scientists, and in linguistic background from monolingual fluent English speakers to multilingual, recent immigrants who may be encountering English for the first time.

My research examines cosmology learning by exploring ways in which visualizations can be used to support learners from mainstream and non-mainstream backgrounds as they move toward constructing a scientific understanding of cosmology content, and developing cosmological literacy. Studying how diverse learners interact with visualizations can inform the development of these materials, and guide educators in deciding how to utilize visualizations in their exhibits and classrooms. In addition, I investigate the institutional context in which these visualizations are embedded, looking for the challenges that arise in presenting cosmology content, and the ways in which learners are served and/or not served by the solutions to these challenges.

Cognitive psychology and conceptual change

In this section I will discuss traditional frameworks for evaluating and describing learning, all of which rely on an out-dated "banking" or "transmission" model of learning that puts an over-emphasis on the performance and attributes of individuals. Not only do these theories provide an incomplete picture of what learning looks like, they create and reify unnecessary divides between "scientific" and "unscientific" that can contribute to student alienation from the world of science.

When policy-makers talk about the goals of science education, they tend to focus heavily on student articulation of very specific content acquisitions. For example in 2013, California fifth graders were expected to "*know* the solar system includes the planet Earth, the Moon, the Sun, eight other planets[11] and their satellites, and smaller objects such as asteroids and comets" (CFCC, 2004, pg. 77). This goal requires students to learn a set of vocabulary words and what category they belong to: e.g. *Neptune* is a *planet* in the *Solar System*. Framing science learning as the acquisition of such content requires a strict dichotomy, both of knowledge (wrong content versus right content), and pedagogical roles (student versus teacher). In this model, the teacher necessarily has ownership over the right answers, and the student seeks to be able to reproduce those answers. This conceptualization has variously been referred to as the "banking" model (Freire, 1970), the "teacher-centered" model (Bransford, Brown & Cocking, 2000), or the "cultural reproduction" model (Bourdieu, 1993). I will use the term "banking model," in an attempt to emphasize both the assumption that learning is linear, and the implications of such an assumption in terms of bestowing cultural privilege. In such a model, education becomes "an act of depositing, in which the students are the depositories and the

[11] In 2005 Pluto was reclassified as a dwarf planet, thus today this standard would read "seven other planets."

teacher is the depositor" (Freire, 1970, p 72). On a large scale, this model perpetuates colonial attitudes about "civilized" and "correct" ways to know and do, and results in the reproduction of existing power structures. In the classroom, this model effectively silences the learner and invalidates his or her opinions and ideas.

The banking model is a reflection of out-dated ideas about learning, rooted in the experiments of psychological researchers in the early twentieth century known as *behaviorists*. Behaviorists like Ivan Pavlov, John Watson, and B.F. Skinner put a heavy focus on the conditions necessary to get subjects to reproduce the correct response, primarily through the application of positive or negative stimuli to encourage or discourage certain types of responses from the subject (Skinner, 1953). For those who theorized learning this way, the process was less important than the production of students who were more likely to reproduce the right answers. Thus behaviorists put little to no focus on individual cognition, but rather on individual performance.

Over the course of the twentieth century, education researchers refocused their attention away from conditioning, toward the cognitive processes of the learner as new content is acquired. This shift was heavily influenced by the work of psychologists Jean Piaget and Bärbel Inhelder, who showed that the way that children respond to stimuli is related to the way in which they think about the world (1969). This view complicated the banking model by taking into account cognition, and allowing for the role of the student in her or his own learning. By the 1980s, most researchers and practitioners framed the learning process as students constructing their own understanding of the natural world, guided by the teacher, a model known as "constructivism," and rooted in cognitive psychology. This model emphasizes the ideas that students already have about the natural world, and the role that this "prior knowledge" takes in the construction of new knowledge.

At face value, constructivism breaks away from behaviorism, giving students ownership of content and softening the strict dichotomy of student versus teacher. However, traditional constructivism still holds to the basic structure of the banking model: there is a right answer, which the teacher probably knows, and the goal is for the student to leave the classroom with the ability to reproduce the right answer. Thus the core model is still one of "banking" the correct answers.

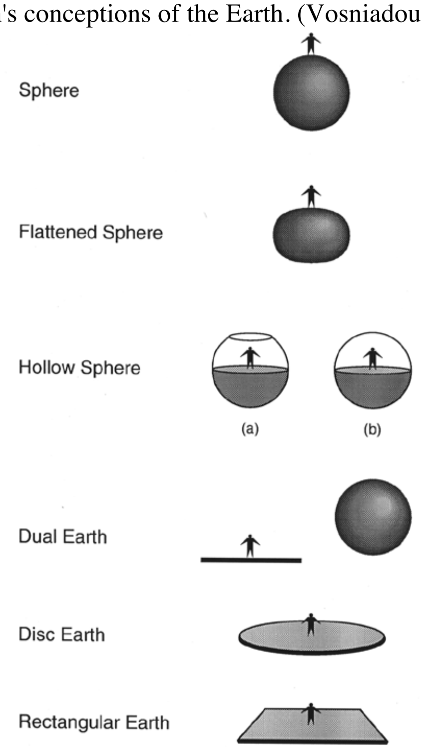
Research from the cognitive psychology perspective seeks to reveal and describe the knowledge that learners bring to the classroom before formal teaching about a science content area has begun, so that teachers will be better informed on how to change the wrong ideas into the right ones. This research typically involves interviews and surveys designed to elicit student's "misconceptions" about a certain topic. One famous example of this type of study was Schneps (1988), who released a video titled "A Private Universe," where high school students and Ivy League graduates alike are unable to reproduce the scientifically agreed upon explanation of why there are seasons. Almost all the students interviewed explain that during the summer the Sun is closer to the Earth, while in winter the Sun is farther.[12] This consistent and resilient pattern of incorrect responses is what cognitive psychologists would call a misconception. Some scholars object to this phrase, preferring less accusatory descriptions like “prior knowledge," “alternative conceptions" or “existing knowledge structures," but the paradigm is essentially the same: there is something in students' heads that may or may not be scientifically accurate, and it is important to reveal that something in order to alter it through teaching. This process of altering the incorrect conceptions and replacing them with the correct ones is known as conceptual change (Strike & Posner, 1985), and this model of learning has come to be known as conceptual change theory (CCT). Teaching for conceptual change requires confronting students with novel tasks for which their existing conceptions are not adequate, creating a “cognitive conflict” that forces them to consider alternative, scientific views of the natural world.

The vast majority of astronomy education literature takes a CCT perspective (e.g. Schneps, 1988; Vosniadou & Brewer, 1992; Prather, Slater & Offerdahl, 2002), seeking out and documenting student misconceptions. As a seminal example of such

[12] The seasons are in fact caused by the relatively stable tilt of the Earth on its axis. This tilt results in a change in the distribution of the concentration of sunlight over the curved surface of the planet as it revolves around the Sun. During summer in the Northern Hemisphere, the Earth is actually further from the Sun than during our winter.

research, Vosniadou & Brewer (1992) used interviews and drawings to probe children's ideas about the Earth. Their work revealed a variety of unscientific models held by schoolchildren, including a hollow earth with the people inside of it, an earth that is round like a pancake, a spherical earth with a sky above it and a spherical earth with all the people standing on top. The taxonomy of misconceptions that Vosniadou & Brewer created from this work are illustrated in Figure 1 below. Using these revealed misconceptions, teachers can purposely design tasks for their students that will produce cognitive conflict, leading to conceptual change; for example a teacher might present students who drew a flat Earth with photographs of the planet taken from space.

Figure 1. Taxonomy of children's conceptions of the Earth. (Vosniadou & Brewer, 1992, p 549)



Conceptualizing visualizations from the CCT perspective

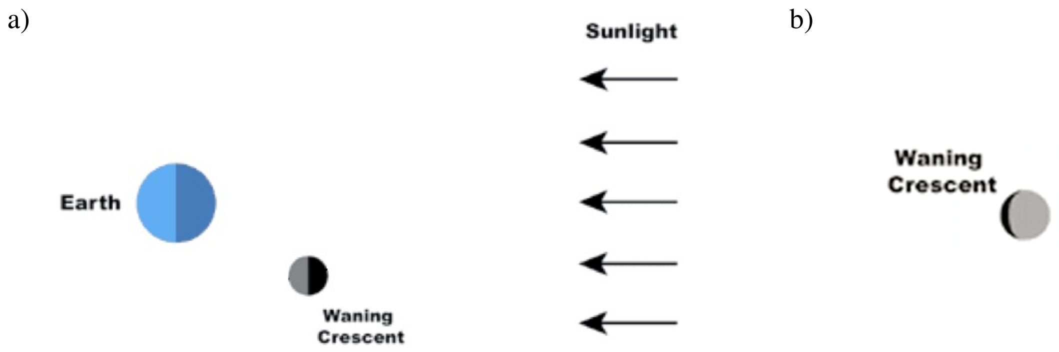
Cognitive psychologists conceptualize visualizations as a type of external representation that stands for something else, thus taking on the function of a sign. These representations are useful learning tools that students can use to lighten their "cognitive load" while performing complex cognitive tasks that can lead to conceptual change.[13] Schnutz et al. (2010) differentiates between two such representations, *descriptive* and *depictive*. Descriptive representations use symbols, which are arbitrary and understood according to convention. Depictive representations use icons, which the authors insist are not arbitrary, but hold a concrete analogous relationship to the actual phenomenon. Depictive representations are more specific than descriptive ones. For example, a descriptive representation might be a sign which states "No Pets." This sign uses language (an arbitrary convention) to get the message across, and applies generally to dogs, cats, birds, etc. On the other hand, a depictive representation might be a sign which has a picture of a large dog with pointy ears with a cross through it. This sign uses an image that matches perception of a dog, and does not require someone to understand written English, however it is very specific. It does not necessarily apply to cats and birds, and perhaps not even to small dogs with floppy ears. Despite their specificity, the

[13] This is know as "conceptual load theory."

authors point out that such depictive representations allow for higher "computational efficiency," and are more useful for making inferences. Dynamic visualizations such as the kind I am investigating are depictive representations, because they present images that match visual perceptions of astronomical objects/systems like stars and galaxies.

While depictive representations are clearly useful tools, not all serve the same function. Vosniadau (2010) suggests that depictive representations can be categorized as either *perceptual* or *conceptual* models, and that this distinction is important. A conceptual model depicts a phenomenon that is not experienced perceptually, or is experienced differently than the depiction, for example a diagram of the Earth, Moon and Sun when the Moon appears to be in the crescent phase from the surface of the Earth, as seen in Figure 2a. A perceptual model matches our egocentric perception of a phenomenon, for example a picture of the crescent Moon in the sky, as seen in Figure 2b. The dynamic visualizations of cosmological phenomena that I investigate in my research depict objects and events that cannot be perceived from an egocentric perspective, only through theory-driven data reconstruction, making them conceptual models. Conceptual models are often counter-intuitive, and require domain-specific knowledge to understand (Vosniadau, 2010).

Figure 2: a) Conceptual model of a waning crescent Moon depicting the Earth and Moon in space, and b) perceptual model of a waning crescent Moon, depicting the apparent shape of the Moon in the sky.



Moving Past Conceptual Change Theory

Conceptual change theory provides a useful framework for describing different kinds of visualizations, and I carry the vocabulary of descriptive, depictive, perceptual and conceptual into my own work. What is valuable about CCT is that it has shown us over and over that learners hold a variety of robust conceptions about the world, and that the process of changing these conceptions is more complicated than just telling someone the right answer. However, when it comes to understanding the hows and the whys of human learning, CCT falls short.

There are five major reasons why I think it is time to move past the conceptual change theory line of research, and the cognitive psychology framework for understanding learning that is associated with it. Firstly, in order to produce generalizable results, CCT research typically assumes that explanations are independent of context. Not only does this ignore the situated nature of cognition (Lave & Wenger, 1991) but it can obfuscate the implications of a set of results. For example, Panagiotaki et al. (2009) sought to investigate claims that the misconceptions revealed by Vosniadou & Brewer (1992) may be the result of research methods (confusing prompts, ambiguous tasks). Their tasks were rephrased to eliminate confusion and the study was replicated. Sure enough, the authors found that the reworded prompts resulted in fewer misconceptions.

Secondly, CCT still relies on knowledge dichotomies, which is not consistent with the constructivist principles upon which it is based (Warren, Ogonowski & Pothier, 2005). If learning is a continuous process of construction and reconstruction, using building blocks of prior knowledge and new knowledge provided by peers and/or a teacher, then what is inside students' heads should vary along a broad, multidimensional spectrum of thinking, not fall into discrete categories of “scientific” and “unscientific.”

Thirdly, CCT investigates individual student performance, on the assumption that the most important processes involved in learning are the higher order mental functioning of the individual. This ignores the fundamental role of social and cultural processes in mediating knowledge construction (Wertsch, 1994; Wells, 2002), and the cognition that occurs regularly in the spaces between individuals, peers and their environment (Vygotsky, 1978).

Fourthly, CCT frames the diversity of everyday experiences and resources brought by diverse learners as discontinuous with scientific reality, and therefore as a barrier to learning, rather than as a resource (Lemke, 2001; Warren, Ogonowski & Pothier, 2005). With this perspective, those students from non-mainstream backgrounds, who come to the classroom with non-mainstream perspectives and ways of knowing, are going to have the most "barriers" to be replaced, require the most "work," and are going to be pushed away from science, where some of their new perspectives could have been valuable resources.

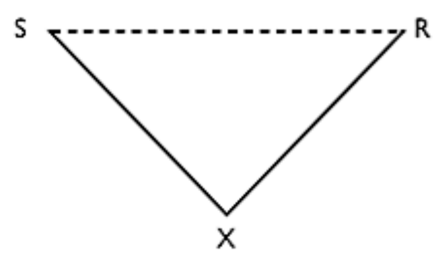
Finally, and perhaps most telling, instruction based on CCT that is designed to challenge and replace conceptions has not been shown to be effective for all learners (Smith et al., 1994; Limón, 2001; Zimmerman & Blom, 1983; Stathopoulou & Vosniadou, 2007). As Lemke (2001) puts it: "An apparent assumption of conceptual change perspectives in science education is that people can simply change their views on one topic or in one scientific domain without the need to change anything else about their lives or their identities…changing your mind is not simply a matter of rational decision making. It is a social process with social consequences." (p 301). Clearly if we seek to both truly understand learning in context, and diversify the landscape of science, we need to take what is useful from CCT and move past it, furthering our research and practice from the banking model to which CCT adheres. As a result many modern science education researchers have turned to sociocultural theory to conceptualize learning (Lemke, 2001; Buxton, 2006), which I have found to be a very productive theoretical frame.

Cultural-Historical Activity Theory (CHAT)

Sociocultural theory originally emerged from the work of Lev Vygotsky in the early decades of the twentieth century. Previously, learning was conceptualized theoretically as a simple transmission of knowledge from a source to an individual subject. In that paradigm, all learning takes place in the mind of the learner, maintaining the traditional Cartesian duality between human consciousness and the rest of the world. Although theorists like Piaget complicated the transmission process to consider cognition (Piaget & Inhelder, 1956), the focus remained on the mind of the individual learner, distinct from societal structures.

Vygotsky's (1978) conceptualization of learning transcended this duality by introducing the concept of mediation to the stimulus-response cycle. Mediation occurs when cultural artifacts act as a two-way filter between the immediate sensory input and the response from the person. This model is commonly depicted as a triad between stimulus, response and cultural artifacts or tools, as in Figure 3 below. Vygotsky's two-dimensional triad model complicates the previously linear relationship between external and internal activity: not only do cultural tools mediate external activity, the external activity in turn mediates internal mental function. For example, the use of language (a cultural tool) to articulate thought (an external human activity) alters the way we think (internal human activity), which we then articulate through language.

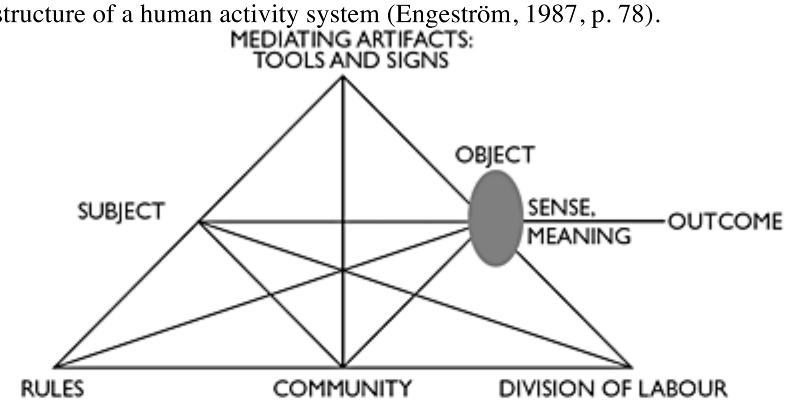
Figure 3. Vygotsky's triad of stimulus (S) and response (R), mediated by cultural artifacts, tools and signs (X).



Vygotsky's work is now considered to be the "first generation" of a sociocultural model of learning known as cultural-historical activity theory, or CHAT (Engeström, 1987). The second generation is attributed to Vygotsky's colleague and student, Alexei Leont'ev. Leont'ev (1974) expanded Vygotsky's model beyond the individual to consider collective human activity. Whereas in Vygotsky's (1978) discussion of learning we could not consider the actions of a learner without including cultural artifacts, Leont'ev proposed that in we cannot consider the mediated actions of the learner without considering the more general collective activity in which both the action and the artifacts are embedded. Leont'ev used the example of the "hunt" to illustrate this: a man performing the action of running toward prey, yelling and waving his arms might confuse the observer, without understanding that the man is trying to scare the prey away from himself and toward the other members of the hunting party, so that they can kill it. The man's actions are embedded in the larger activity of the hunt, and while the goal of his action is to frighten the animal, the true object of his activity is to feed his family. Essential to understanding the difference between actions and activity are the ways in which humans divide labor, either implicitly or explicitly; some hunters take on the role of "beater," while others take on the role of "shooter." In the classroom, a student and a teacher take on very different roles, and may be engaged in very different actions in the classroom (listening to a lecture, giving a lecture), oriented toward very different short term goals (understanding the information, communicating the information), but together these actions are embedded in the same activity, oriented toward the same goal (student understanding of the information to the point that the student can perform at a certain level on an assessment).

Yrjö Engeström (1987) refined and expanded on this model in the second half of the twentieth century with the introduction of a graphical model of the collective activity system that emphasized the "relationship" between mediation and the other components of an activity system (Engeström 1999, p 29). Such a model is shown in Figure 4 below. The uppermost tip of this triangle is a reformulation of Vygotsky's original triad, representing the mediated action of an individual (or several individuals). The base of the triangle represents the rest of the collective activity system, in which the action is embedded. The activity is directed toward an "object," which is a distinct idea from the more short term "goals" of individual actions. The oval indicates that object-oriented actions are always, explicitly or implicitly, characterized by ambiguity, surprise, interpretation and *sense-making* (Engeström, 1999).

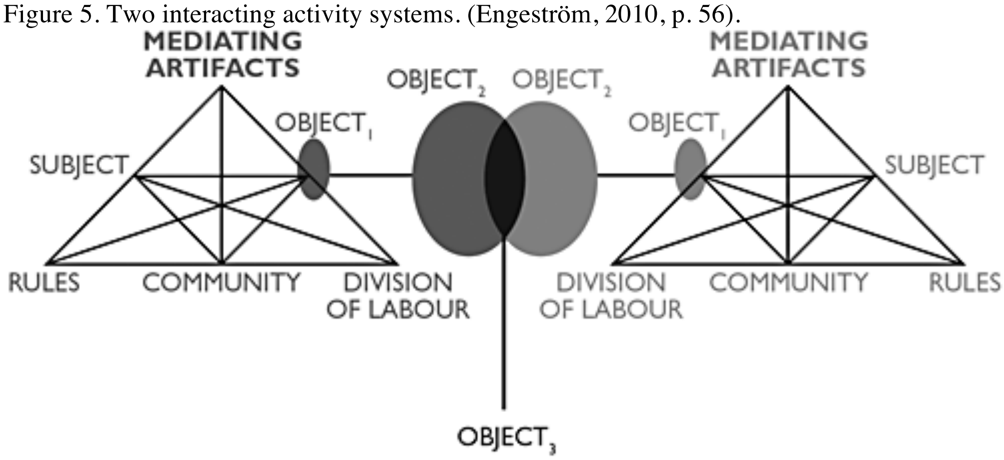
Figure 4.The structure of a human activity system (Engeström, 1987, p. 78).



This second generation of cultural-historical activity theory has been the basis of much research on learning over the past several decades. Research that takes on CHAT as a theoretical approach should take the activity system as a unit of analysis, thus reframing social, historical and cultural context as an integral part of the phenomenon under study, rather than as a "container" for that phenomenon, or something tangential to it.

As sociocultural theory moved out of Soviet Russia, and became a more popular theoretical approach internationally, critics began to point out that CHAT was insensitive to diversity, and thus not truly applicable in cross-cultural contexts (Cole, 1988; Griffin & Cole, 1984; Engeström, 2010). In response to this, a third generation of activity theory has begun to emerge, one in which analysis takes into account dynamic networks of activity systems, with a focus on how these systems dialogue with and challenge one another (Engeström, 2010). The graphical model for understanding a simple (n=2) network of activity systems is shown in Figure 5 below. Within such a model, the object motivating activity becomes a "moving target," a complex and shifting element constructed, deconstructed and reconstructed by activity systems and the interactions between them.

Figure 5. Two interacting activity systems. (Engeström, 2010, p. 56).



Engeström (2010) stresses that such systems are inherently "multi-voiced," incorporating multiple perspectives and interests, and situated within communities with varied repertoires of practice (Gutierrez & Rogoff, 2003; Lave & Wenger, 1991). They are constructed within a historical context and shaped by the passage of time, and can only be understood "against their own history." Historicity is particularly important when considering those places where tension and contradiction arises. Contradictions, defined by Engeström (2010) as "historically accumulating structural tensions within and between activity systems," are a vital location for understanding the dynamics of these systems and the networks in which they are embedded. It is through contradictions and the reactions they provoke over time, that activity systems are modified and changed significantly, and at the points of change are the potential for new forms of activity, or *expansive learning*.

In this dissertation, I use all three generations of activity theory to inform my methodology, by looking at mediational cues involved in their interpretation (first generation), making sense of visualizations in small groups (second generation), and redefining shared objects arising from contradictions around visualizations (third generation). I will begin by situating visualizations within the CHAT framework, drawing from the literature on human-computer interactions.

Visualizations as tools within the activity system

According to Lemke (2001), sociocultural theory has shown us that "the core sense-making process at the heart of scientific investigation…critically involve instrumentation and technologies, in effect distributing cognition between persons and artifacts, and persons and persons, mediated by artifacts, discourses, symbolic representations, and the like" (p 298). Visualizations are one such technology, a means for distributing cognition, heavily mediated by symbolic representation among other things. Although there is little to no literature looking at visualizations from the perspective of CHAT, there is a solid body of research on the role of computers in human activity. Computers are very different than visualizations in many ways; for example computers are "interactive" learning tools, in that the user can manipulate the stimuli being offered by the computer in real time, while the visualizations studied here present stimuli that cannot be directly manipulated by the passive observer. Still, I believe that the shared novelty of computer and visualization technology, in addition to the spaces and contexts in which they are often presented (screens in classrooms, museums, etc) make this a fruitful connection to draw.

Like visualization research, early research on learning using computers came out of cognitive psychology, and focused primarily on individual user-computer interactions. However, in the mid 1990s, learning scientists began to realize that both human beings and computers developed and are developing in the process of cultural history, and thus can only be understood within the context of human activity (Kaptelinin, 1996). While earlier research focused only on human actions (e.g. she used the mouse to click on the word processor icon), Leont'ev suggested that actions cannot be understood without understanding the object-oriented activity in which they are embedded (e.g. she wants to tell a story). This required a shift in perspective away from "computer-human-interaction," to "computer-mediated-activity" (Bødker, 1996). In the same way, rather than theorize the human-visualization-interaction, I focus on human activity mediated by visualizations, and activity oriented toward making sense of the visualizations. In other words, I see the visualization as taking on a dynamic role within the activity system, both mediating, and being mediated, orienting, and being oriented toward.

Research Overview

My research comes from a sociocultural perspective, which sees learning as a complex, situated, social process (Vygotsky, 1978; Lave & Wenger, 1991). To support this process, we need to understand it, and to understand it, we need to identify and describe the activity systems involved in the learning. By focusing on mediation, sense-making, and context, I aim to move cosmology education research further from the tradition of uncovering learners' incompetence, toward uncovering learners' competence, and "exploring ways in which such competence can be supported to promote development of robust understanding of the physical world" (Warren et al., 2005, p 122). My methodological goal is to improve access to STEM content through the development of cosmology visualizations, rather than perpetuate current patterns of access.

Research Questions

To understand better how to design visualizations that work toward breaking cycles of power and access in the sciences, I orient my work to following "meta-question": *How might educators use visualizations to support diverse ways of knowing and learning in order to expand access to cosmology, and to science?* This question engenders several general lines of inquiry.[14] First: what mediational cues best support all learners in figuring out visualizations? This line of inquiry suggests simple experimental studies that test the effect of changing various design elements on individual learners' ability to reproduce scientific explanations of the visualization. From this line of inquiry, we can learn about how to make basic modifications to visualizations that will enhance their usefulness as learning tools. But this does not tell us about the learning process, and thus the second line of inquiry asks: how do visualizations support the cosmological sense-making[15] of diverse learners? This suggests a qualitative analysis of learner activity oriented toward making sense of cosmology visualizations. From this line of inquiry, we can learn more about how to use visualizations in learning contexts, and their potential as learning tools for culturally and linguistically diverse students. The final line of inquiry takes a broader perspective, looking at some of the challenges and realities of creating, implementing and assessing visualizations in context by asking: how do

[14] Keep in mind that these are not research questions yet, but simply research pathways that suggest three distinct methodologies.

[15] I define cosmological sense-making as activity mediated by the concepts and practices associated with cosmological literacy.

visualizations function as learning tools in an institutional context? The importance of context in this line of inquiry suggests a case study design to investigate the use of visualizations within an institution where visualizations are being used and/or produced.

In the chapters that follow, I follow each of these lines of inquiry from a sociocultural perspective to address my meta-question. The methodologies that emerged from these three lines of inquiry informed the development of more concrete research questions, below. Each of the following research questions corresponds to a self-contained chapter:

1) Can mediational cues like color affect the way learners interpret the content in a cosmology visualization?
2) How do cosmology visualizations support cosmological sense-making for diverse students?
    a. What concepts and practices associated with cosmological literacy emerge when community college students are making sense of visualizations while engaged in object-oriented activity in small groups?
    b. What strategies are employed by diverse learners in a community college classroom to make sense of cosmology visualizations?
3) What are the shared objects of dynamic networks of activity around visualization production and use in a large, urban planetarium and how do they affect learning?

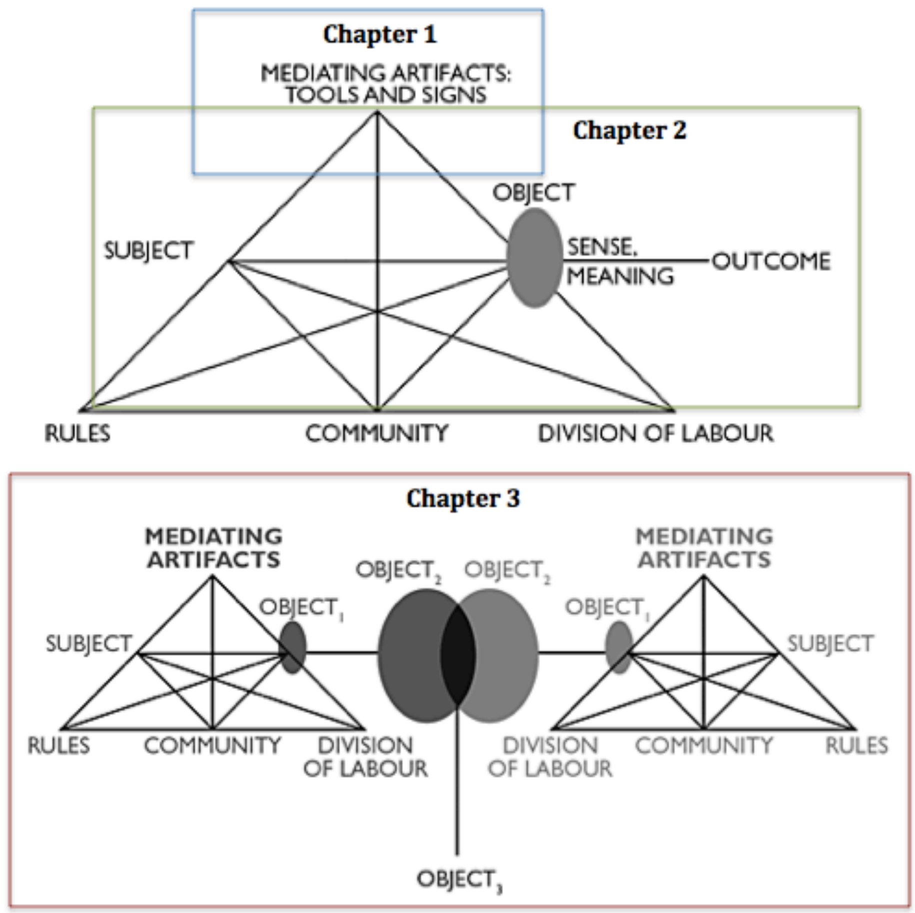
a. How does the historical context of the planetarium create contradictions in the activity and discourse around visualizations, and how does manifest itself in the object of activity?
b. What is the object of visualization-mediated visitor activity at the planetarium, and how does this fit within the larger network of activity?
c. What knowledge resources are visitors drawing on in order to mediate activity around figuring out visualizations?

Research Paradigm

My research comes from a pragmatic philosophical paradigm, which rejects the incompatibility of post-positivist and interpretive methodologies. Pragmatists take “the current meaning or instrumental or provisional truth of an expression…to be determined by the experiences or practical consequences of belief in or use of the expression in the world” (Murphy, 1990, cited in Johnson & Onwuegbuzie, 2004). This outcome-oriented perspective accepts the validity of both experimental and interpretive methods, suggesting that the researcher “choose the combination or mixture of methods and procedures that works best for answering your research questions” (Johnson & Onwuegbuzie, 2004). Thus while I locate my research within a theoretical perspective that sees knowledge as situated, I do not see this stance as invalidating the usefulness of statistical analysis in attempting to understand social phenomena. The result is a mixed-methods design (Sweetman, Badiee & Creswell, 2012), where qualitative and quantitative data collection are occurring concurrently to address my research goals.

Sociocultural theory emphasizes that all human activity functions on multiple scales, "from the physiological, to the interactional to the organizational to the ecological" (Lemke, 2001), which informed my decision to collect data at multiple levels: from individuals, to families/friend groups, to the institution, using a combination of surveys, interviews, activities, and observations, suggesting a concurrent mixed-methods design. My progressively wider scope of analysis echoes the development of activity theory over the past one hundred years, as outlined above, starting with Vygotsky's triad of stimulus, response and mediation, expanding outward to include parts of the second generation activity triangle, and finally incorporating third generation networks of activity connected by shared objects. Chapter one addresses the impact of mediational cues like color on learner responses to a survey after viewing a visualization (e.g. Carvalho & Sampaio, 2006)). Chapter two addresses the activity of diverse learners, in particular with regards to their sense-making during object oriented activity (e.g. Moschkovich, 2002). Chapter three looks at a dynamic network of activity systems through the third generation CHAT lenses of historicity, contradictions, multi-voicedness, and the potential for expansive learning (e.g. Ash, 2014). A graphical overview of the way my research design sits within activity theory can be found in Figure 6. In the next section I summarize each chapter briefly to provide a broad overview of the structure of the dissertation.

Figure 6. Dissertation design within the structure of activity theory.



Dissertation Summary

The three chapters of this dissertation can be treated as self-contained research papers, each following one of the lines of inquiry outlined above, situated within progressively expanded views of the CHAT framework. In the first chapter I use quantitative methods to investigate how 122 post-secondary learners are relying on color as a mediational cue to interpret dark matter in a cosmology visualization. I employ an alternative treatment post-test only experimental design, in which members of an equivalent sample are randomly assigned to one of three treatment groups, followed by treatment and a post-test. Results indicate a significant relationship between the color of dark matter in the visualization and survey responses, implying that aesthetic variations like color can have a profound effect on learning activity oriented toward interpreting a dynamic cosmology visualization. I look more closely at such activity in chapter two.

In the second chapter I look at how the visualizations are used by small groups of community college students to make sense of cosmology visualizations. Because sociocultural theory tells us that learning is primarily an active, social process, and that knowledge is socially constructed; and because visualizations are primarily a passive, individual medium (Small & Plummer, 2010), I have developed an activity that encourages students to work collaboratively, and engage actively toward the construction of an "improvable object" (Wells, 1999; 2002). I present evidence that visualizations can scaffold *cosmological sense-making*, which I define as engaging in object-oriented learning activity mediated by concepts and practices associated with cosmological literacy. The visualizations allowed the students, many of whom were language minorities, to grapple directly with cosmology content while practicing the language of science. The students used hybrid language and analogy to make sense of the visualization. In light of these findings, I argue that carefully incorporating visualizations into learning environments can improve access to cosmology content for learners, particularly those who come from a cultural or linguistically diverse background. I investigate just such a learning environment in chapter three.

In the third chapter I present a case study of an urban Planetarium trying to define its goals at a time of transition, during and after the development of a groundbreaking planetarium show. I analyze the dynamic, historical patterns activity at the Adler Planetarium, where cosmology visualizations play an increasingly central role in the production of planetarium shows and exhibits. My analysis reveals several historical contradictions that appear to drive a shift toward affective goals within the institution, and driving the implementation of visualizations, particularly in the context of immersive planetarium shows. In my discussion, I problematize this result by repositioning the shift toward affective goals in the context of equity and diversity.

Table 1 provides an overview of this dissertation summary. While each chapter follows a unique line of inquiry, with its own theoretical framework, methods, and results, taken together they tell us an important story about dynamic visualizations as tools for learning. Visualizations can present complex content, making the invisible visible and the unimaginable imaginable. This dissertation reveals the potential of such a medium, as well as the challenges, and concludes with concrete recommendations for the design and dissemination of visualizations across settings.

Table 1. Dissertation summary.

Chapter Title	The Effect of Mediational Cues on Learner Interpretation of a Cosmology Visualization	Community College Students Making Sense of Cosmology Visualizations	Contradictions, Historicity and Learning at an Urban Planetarium
Research Methods	Survey methods	Analysis of activity	Case study
CHAT framework	First generation: mediational cues	Second generation: sense-making in activity	Third generation: shared objects in dynamic networks of activity
Research Question	Can mediational cues like color affect the way learners interpret the content in a cosmology visualization?	How do cosmology visualizations support cosmological sense-making for diverse students?	What are the shared objects of dynamic networks of activity around visualization production and use in a large, urban planetarium, and how might they affect learning?

Chapter One: The Effect of Mediational Cues on Learner Interpretation of a Cosmology Visualization

In this chapter I use quantitative, experimental methods to investigate how 122 post-secondary learners are relying on color to interpret dark matter in a cosmology visualization. I employ an alternative treatment post-test only experimental design, in which members of an equivalent sample are randomly assigned to one of three treatment groups, followed by treatment and a post-test. Results indicate a significant relationship between the color of dark matter in the visualization and survey responses, implying that aesthetic variations like color can have a profound effect on audience interpretation of a dynamic cosmology visualization.

Introduction: Dynamic visualizations

Dynamic visualizations[16] are learning tools for presenting complex and rigorous science content, without high linguistic demand. They are flexible media that can bring the hidden aspects of the Universe into students' experience, and inculcate students into some of the tools of science. Multi-media simulations and visualizations have been shown to support science achievement in biology (e.g. Kiboss, Ndirangu & Wekesa, 2004) and chemistry (e.g. Ardac & Akaygun, 2004), so there is precedent to suppose that they might be used to support learning in cosmology. Visualizations can take advantage of "the power of alternative formats in communicating ideas" (Lee & Fradd, 1998, p 17), especially for learners who come from non-mainstream cultural and linguistic backgrounds. We also know that such simulations and visualizations can serve to help students generate their own mental images, and deepen their engagement in conversations around the content (Wu, Krajcik, & Soloway, 2001).

Over the last decade, advancements in technology have made these tools easier to produce and disseminate; modern visualizations are visually stunning and incredibly accurate depictions of the Universe. As a result, real scientific

[16] Although I use the term "visualization" for the remainder of the chapter, I am referring to animated data simulations, or dynamic visualizations, not static representations of data.

visualizations have become one of the most utilized media for presenting astronomy content in both informal settings and classrooms. Even astronomy education in the K-12 classroom increasingly relies on high tech computer visualizations (Yair, Mintz, & Litvak, 2001).

Typically the scientists who analyze the data are producing these visualizations in ways that make sense to them, and take advantage of new technology. Visualizations are socioculturally situated tools (Vygotsky, 1978), and thus we cannot take it for granted that what makes sense to some will make sense to others. There is very little research that provides guidance for how to produce visualizations in a way that makes them more effective tools for supporting learning. I am interested in better understanding visualizations as tools that support the development of cosmological literacy (Engeström, 1987; Nardi, 1996) in order to guide visualization production to expand access to cosmology content.

Visualizations and Color

Learners bring a lifetime of experience and knowledge to the table (Piaget & Inhelder, 1969), which makes a profound impact on how they interpret their world. As a classic example, when presented with two images of a star, one red and one blue, learners will take blue to mean cold and red hot, even after being taught the opposite (Carvalho & Sampaio, 2006). This is because our sinks and showers, to which we are exposed multiple times every day, tell us otherwise. A lifetime of prior associations is a powerful thing, and without attention to the social and constructivist nature of learning[17] even the best explanations of color and temperature can be ineffective in convincing learners that blue indicates a higher temperature than red. It is vital that educators be aware of associations like this one, and work patiently with students to support a deeper understanding of science content, especially for students from non-dominant cultural and linguistic backgrounds (Lee & Fradd, 1998, Solano-Flores & Nelson-Barber, 2001).

It is logical to assume that such prior associations with color come into play in a variety of visualizations, in particular for the invisible aspects of the Universe, for which all color assignments are inherently false. For example, dark matter is vital to our understanding of the Universe (Abrams & Primack, 2011) and yet it is invisible. Understanding the invisible aspects of the Universe is one facet of cosmological literacy (see introduction). But there is no research that suggests how to illustrate dark matter in a way that makes sense to people. The research I present here investigates the effect of color on learners' interpretation of dark matter in a cutting

---

[17] As discussed in the introduction, my work comes from the neo-Vygotskian perspective that all knowledge is socio-culturally constructed and that learning is situated. From this perspective, teaching should be aimed at supporting students as they construct understanding through activity that is mediated by social and cultural tools (Vygostky, 1978; Engeström, 1987).

edge visualization produced by the University of California High Performance Astro-Computing Center (HiPACC) for the Adler Planetarium. The visualization, known as the Constrained Local UniversE Simulations (CLUES), reproduces the formation of dark matter structure of our local Universe over time.

The version of CLUES produced for the Adler Planetarium was originally rendered in white and blue, with white representing dark matter and blue representing empty space (as shown in Figure 7). In the summer of 2011, I spent a month at the Adler gathering pilot qualitative data about CLUES and other visualizations embedded in their new planetarium show. During this time, I noticed anecdotally that several audience members appeared to be confused by which part of the visualization was dark matter. This led me to the following quantitative research question: Can mediational cues like the color of a cosmology visualization affect the way learners interpret the content?

The quantitative research reported here was conducted in spring of 2012, based on data collected from college students in California (both at a large research university, and a rural community college).

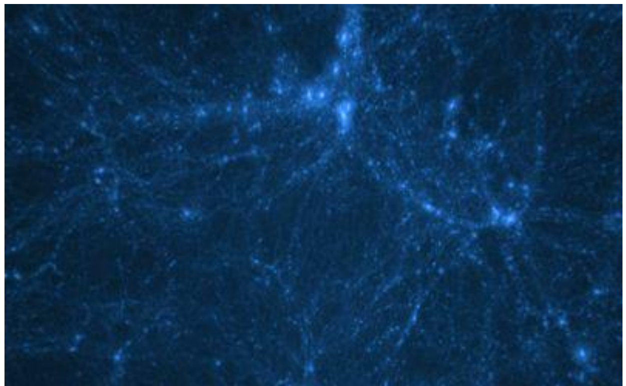
Methods

Research Design

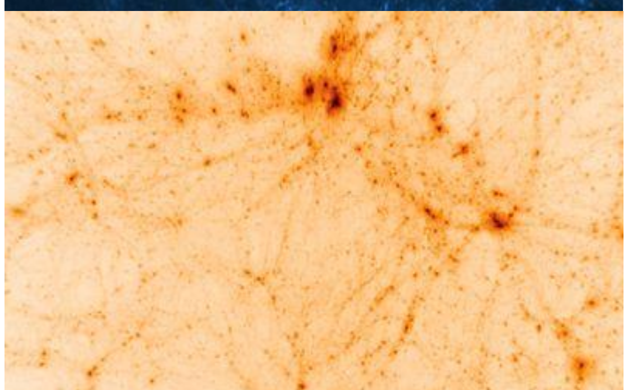
To test the effect of color changes on learner interpretation, I designed an internet survey, which is attached in Appendix A. I gave this survey to 122 post-secondary students in California. The survey played the CLUES visualization with accompanying explanatory text,[18] and then asked participants to respond to questions about the visualization. Three versions of CLUES were tested: the original version, which I refer to as "CLUES blue," a color-inverted version in which the dark matter looks brownish-orange, which I call "CLUES peach," and a color-inverted version where dark matter is represented in black on a white background, which I call "CLUES b&w." Snapshots from each version are included in Figure 7.

[18] The explanatory text is included in Appendix A. The full visualization can be seen in its original form at: (http://hipacc.ucsc.edu/v4/media.details.php?mediaID=MzRiNjNkODYxYTIz) or in all three forms on the online version of the survey instrument (www.buckfilm.com/survey).

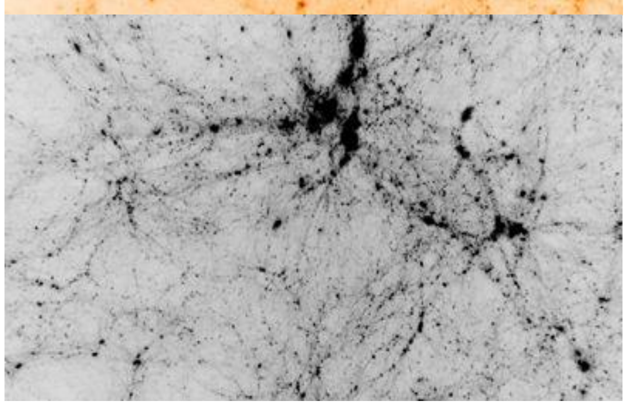
Figure 7. Snapshots of the three versions of CLUES tested. From top: CLUES blue, CLUES peach, and CLUES b&w. Courtesy of UC-HiPACC, NASA and the Adler Planetarium



Snapshot from CLUES Blue



Snapshot from CLUES Peach



Snapshot from CLUES B&W

The research presented here is characterized by an alternative treatment post-test only experimental design (Creswell, 2003), in which members of a sample are randomly assigned to one of three treatment groups, followed by treatment and a post-test. This design is illustrated in table 1. Participants were randomly assigned a different treatment by a random number generator built into the entrance website. Each group was shown a different version of the CLUES visualization with the same explanatory text printed below, and then asked a series of standardized questions to assess their interpretation of the visualization. These included four multiple choice questions requiring participants to choose the color corresponding to 1) dark matter, 2) stars, 3) empty space, and 4) hydrogen gas, or to indicate that the component in question was not visible in the visualization.

Table 2 Experimental design overview. Xn represents the three treatments, CLUES blue, CLUES peach, and CLUES b&w.

Group A:	Random Assignment	-----------------	Treatment X1	-----------	Observation
Group B:	Random Assignment	-----------------	Treatment X2	-----------	Observation
Group C:	Random Assignment	-----------------	Treatment X3	-----------	Observation

Other questions included gender, race/ethnicity, first language, education level, familiarity and interest in science and astronomy, and familiarity with similar visualizations. Those participants who responded that they had been diagnosed with colorblindness, or suspected they might be colorblind (n=2), were removed from the sample.

Sample

Participants (n=122) were drawn from four-year undergraduate students in education classes, and community college students entering an introductory astronomy class. 260 students were given the address of the survey, and asked to take it on their own time. Response rate was 47%. The ethnic and linguistic makeup of each treatment group was roughly equivalent, as shown in Figure 8 below. This equivalence is a result of randomization, and lowers the probability of bias among the sample groups. In an attempt to limit sample bias among the entire sample, participants were recruited from both a major research University, which is majority White and English Native, and a rural community college, which is majority Latina/o and has a high percentage of English Learners. The result was a sample that more closely mirrored the demographics of California than a study that focused on only one school, especially for these two groups (Whites and Latina/os). The ethnic makeup of the entire sample is summarized in Table 2. For comparison, the ethnic makeup of California according to the 2011 census is listed in Table 3.

Table 2. Racial/ethnic self-identification of the entire sample.

Racial/ethnic identification for the entire sample	Percent of Sample
Black	2%
Asian	13%
Multiracial	14%
Hispanic/Latino	27%
White	40%

Table 3. From the U.S. Department of Commerce United States Census Bureau.

Racial/ethnic identification for the state of California	Percent of Population
Black	6.6%
Asian	13.6%
Multiracial	3.6%
Hispanic/Latino	38.1%
White	39.7%

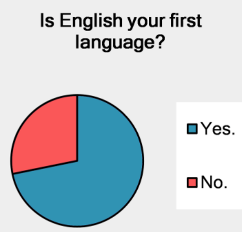
Figure 8. Self reported ethnic and linguistic demographics for each treatment group.

CLUES Blue

With which ethnic background do you most closely identify:

Answer Options	Response Percent
Hispanic/Latino	35.9%
Black	2.6%
White	38.5%
Asian/Asian American	7.7%
Pacific Islander	0.0%
Native American/American Indian/Alaskan Native	2.6%
Multiracial	15.4%
Other (please specify)	7.7%

clues bw



With which ethnic background do you most closely identify:

Answer Options	Response Percent
Hispanic/Latino	28.9%
Black	0.0%
White	42.1%
Asian/Asian American	18.4%
Pacific Islander	0.0%
Native American/American Indian/Alaskan Native	0.0%
Multiracial	10.5%
Other (please specify)	5.3%

clues peach

With which ethnic background do you most closely identify

Answer Options	Response Percent
Hispanic/Latino	19.4%
Black	3.2%
White	58.1%
Asian/Asian American	9.7%
Pacific Islander	0.0%
Native American/American Indian/Alaskan Native	0.0%
Multiracial	12.9%
Other (please specify)	3.2%

Measures

The treatment variable is a nominal indication of which of the three versions of CLUES a participant was shown (see figure1), either “Blue,” “Peach,” or “BW.” Outcome variables included nominal responses to each of the four specific visualization interpretation questions, which asked participants to identify: 1) dark matter, 2) stars, 3) empty space, and 4) hydrogen gas.[19] Each question asked participants to choose between the structure shown in CLUES, the background, or to indicate that what was being asked about was not present in the visualization.

Finally, for ease of analysis, I created an ordinal variable summarizing each participant's responses to the visualization interpretation questions, which I called the "interpretation index." To create the interpretation index, I dichotomized participant responses to the four visualization interpretation questions as either "scientific" (1) or "unscientific," (0) based on their agreement with the intentions of the creators of the visualizers (i.e. structure is dark matter, background is empty space, no gas or stars visible), and summed the scientific responses for each participant, resulting in an ordinal number from 0 to 4, with 0 indicating no scientific responses, and 4 indicating that all four responses as scientific. This index serves to summarize roughly how well the participant has understood the visualization as a whole.

Data Analysis and Results

To test for independence between variables, I used Pearson's Chi-Squared test. For this test, a chi-squared probability (p) of less than or equal to 0.05 (meaning that there is a 5% chance that the relationship between categorical variables is by

[19] Only dark matter and empty space were intentionally represented in the CLUES visualization.

chance) is commonly taken as justification for rejecting the null hypothesis. Chi-squared testing was used to test the following null hypothesis: the data collected meets the distribution of a population where there is no association between CLUES version and survey responses; in other words, a participant is equally as likely to interpret the CLUES visualization scientifically regardless of the colors used in the visualization. In this case, scientific interpretation is quantified by the interpretation index, a summary variable of correct responses to four interpretation questions. 91 participants responded to every question in the survey, and were used for the bulk of the statistical analysis. Table 4 below summarizes how many participants received interpretation index scores of 0,1, 2, 3 and 4 for each of the three CLUES visualizations. Recall that a score of 0 indicates no scientific responses, while a score of 4 indicates that all four questions were answered scientifically.

Table 4 Summary of interpretation index scores across treatment groups.

Interpretation Index:	0	1	2	3	4	Sum
CLUES Blue	8	6	13	3	3	33
CLUES Peach	3	5	6	8	6	28
CLUES BW	2	4	10	3	11	30
Sum	13	15	29	14	20	91

Results of chi-squared testing are summarized in Table 5, below. Each of the p-values in Table 5 represents the probability that the observed distribution of frequencies corresponds to a distribution that matches the null hypothesis. In other words, there is only a .03% chance that the higher frequency of correct responses to the question about dark matter from those who saw a visualization where the original colors were inverted is due to sampling error from a population where the frequencies are actually randomized. Thus it can be said with confidence that the color of the CLUES visualization has an impact on learners' interpretation of dark matter in that visualization. However, the claim cannot be made that the color of the CLUES visualization has an impact on learner's interpretation of empty space in that visualization, or ability to state that hydrogen gas is not present.

Table 5 Summary of calculated p-values.[20]

p-value for identifying dark matter as structure (significant)	0.000361
p-value for identifying stars as not present (significant)	0.048080143
p-value for identifying empty space as background (not significant)	0.638539422
p-value for identifying hydrogen gas as not present (not significant)	0.490919793

My results indicate that the there is a relationship between which color version of CLUES the participant viewed and how that participant interpreted the visualization. Respondents who saw the original version of CLUES (n=33), which used white to indicate dark matter and blue to indicate empty space, were almost four times more likely to misidentify dark matter in the visualization than those who saw a

---

[20] The p-value is defined as the probability of obtaining a test statistic result at least as extreme as the observed value. In this case the test statistic was chi-squared. A p-value less than or equal to .05 is typically considered a significant justification for rejecting the null hypothesis.

version of CLUES where dark matter was indicated by a color that was darker than the background (n=58) as shown in the pie charts in Figure 9. Chi-squared testing indicated that this result is unlikely to be by chance. Respondents who saw the original version of CLUES were also only half as likely as other participants to correctly indicate that there were no stars present in the visualization.

The interpretation index serves as an ordinal variable indicating how well the participant has understood the visualization. Participants who saw a version of CLUES where dark matter was represented by a dark brown color (CLUES peach) were twice as likely to receive the highest interpretation score than those who saw the original visualization (CLUES blue), as shown in Figure 10. Participants who saw a version of CLUES where dark matter was represented by black on a white background (CLUES bw) were more than three times as likely to receive the highest interpretation score than those who saw the original visualization (CLUES blue), also shown in Figure 10. This relationship between the treatment group and the interpretation index was significant ($p<.05$).

Figure 9. Colors chosen by respondents for both dark matter and stars for each CLUES sub-sample. Correct responses (in green) for each visualization for dark matter are (in order): white, brown, and black. The correct response (in green) for stars is that there are none visible. Note that the majority of participants misidentified both dark matter and stars in CLUES Blue. On the other hand, the majority of participants correctly identified both dark matter and stars in CLUES BW.

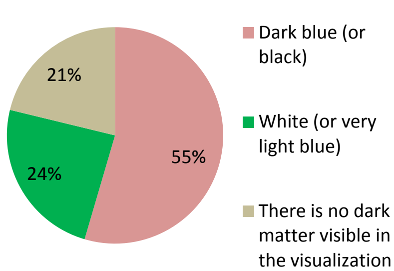
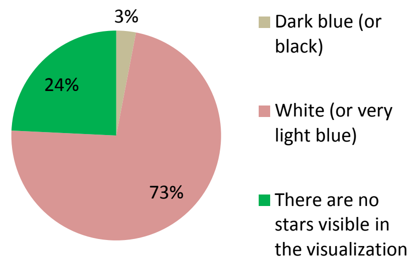
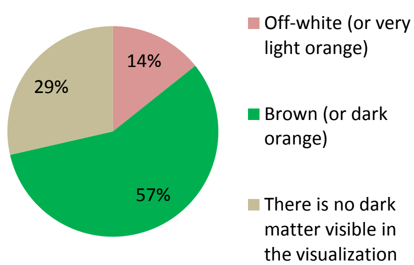
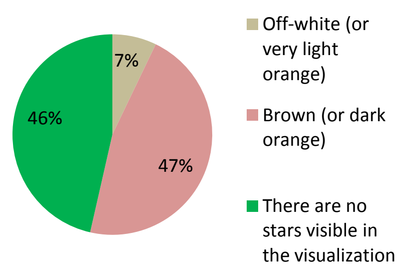
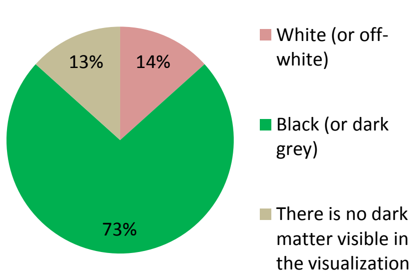
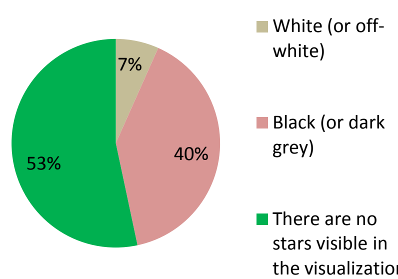
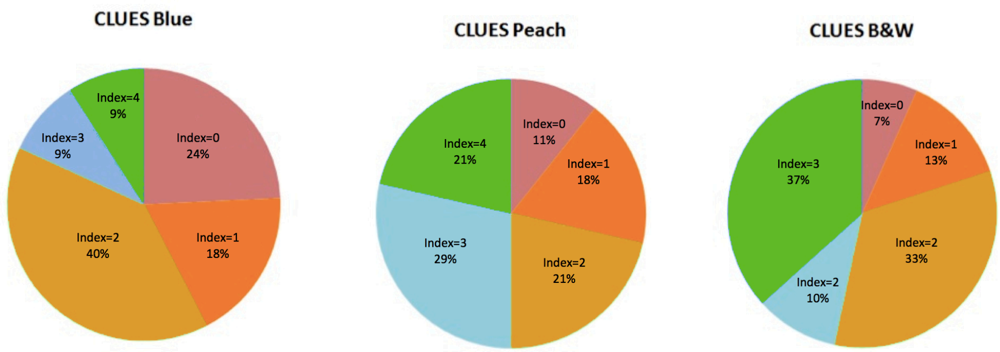
<table>
<tr><th>CLUES</th><th>Using what you remember from the cosmology presentation, what color is the dark matter in the image above?</th><th>Using what you remember from the cosmology presentation, what color are the stars in the image above?</th></tr>
<tr><td>Blue</td><td>
</td><td>
</td></tr>
<tr><td>Peach</td><td>
</td><td>
</td></tr>
<tr><td>B&W</td><td>
</td><td>
</td></tr>
</table>

Figure 10. Interpretation indices for each treatment group (Blue, Peach, B&W). Index=0 represents respondents who interpreted the visualization with the least accuracy, Index=4 represents respondents who answered all four interpretation questions correctly.



Implications and Next Steps

The major implication of these results is that seemingly superficial design choices like the color chosen to represent various aspects of the Universe in a cosmology visualization can have an effect on how learners interpret that visualization. This effect is particularly strong for identification of dark matter, perhaps because learners make a rational association between the term "dark" and darker colors. Similarly, the fact that learners identified dark matter as "stars" in the CLUES Blues simulation can be attributed to a rational prior association between bright points of light and stars. The following quote from a young girl who had just seen a similar visualization illustrates the rationality of such an association:

Z: What do you think the white stuff is made of?
Young girl: Stars?
Z: What makes you think they are stars?
Young girl: Cuz stars I look at up at the sky from my house and I see stuff like that, it looks like miniature Suns, which…are bulbs of light

Right now, visualization development that comes out of scientific research typically does not include research on interpretation, and thus decisions such as color and speed are made by scientists and artists without the benefit of learner data. This suggests the need for more research on learning using visualizations, both quantitative and qualitative.

Well-designed learning tools in science educational settings require an ongoing cycle of research and implementation. But too often, such a cycle serves to perpetuate the status quo: researchers sample a mainstream demographic because they are most visible in classrooms and informal education settings, and then based on that research mainstream learners are better served, perhaps at the detriment of other, less visible learners. The cycle described above is echoed in persistent inequitable access throughout Science, Technology, Engineering and Mathematics (STEM).

Visualizations have the potential to be a very powerful medium for presenting cosmology, a field that can seem removed from everyday experience without a visual connection to the content. But to make visualizations a more effective medium for communicating cosmology to all learners, decisions should be guided by research that includes diverse learner voices. In the next chapter, I expand my view from product to process by looking at the activity of diverse learners as they engage in cosmological sense-making in activity oriented toward interpreting and re-creating visualizations.

Chapter Two: Community College Students Making Sense of Cosmology Visualizations

In this chapter I look at how visualizations are used by small groups of community college students to make sense of cosmology visualizations. I present evidence that visualizations can support *cosmological sense-making*, which I define as engaging in object-oriented learning activity mediated by concepts and practices associated with cosmological literacy. The visualizations allowed the students, many of whom were language minorities, to grapple directly with cosmology content while practicing the language of science. This process was facilitated by a drawing activity that served as an improvable object, encouraging cosmological sense-making. The students used hybrid language and analogy to make sense of the visualization, describing the patterns and dynamics of the system even when they did not articulate scientific vocabulary like “gravity.” This could be due in part to the potential for visualizations to present complex information without necessitating complex vocabulary. In light of these findings, I argue that carefully incorporating visualizations into learning environments can improve access to cosmology content for learners, particularly those who come from cultural or linguistically diverse backgrounds.

Introduction: Inequitable access to science

Despite decades of effort to promote "science for all" (Barton, 1998), culturally and linguistically diverse learners remain underrepresented in STEM post-secondary education (Stoddart, Pinal, Latzke, & Canaday, 2002). This pattern of inequity can be attributed to a history of compounding educational, economic and social deficits (Ladson-Billings, 2006), including inequitable access to educational opportunities throughout K-15, (Mosqueda, Téllez & Moschkovich, 2011) where students from non-dominant cultural and linguistic backgrounds persistently and disproportionally lack access to rigorous content in science (Oakes, Ormseth, Bell, & Camp, 1990), and are more likely to be subjected to curriculum designed to "teach-to-the-test" (Kozol, 1988). In urban schools where diverse students have historically been most concentrated, we know that high-quality instructional materials that meet current science education standards have been limited (National Science Foundation [NSF], 1996).

In addition to those groups defined by traditional markers of diversity like race and ethnicity, learners from non-dominant linguistic backgrounds (NDLB)[21] are

[21] I choose to use NDLB to identify these learners in order to emphasize the heterogeneity of linguistic backgrounds that differ from what is considered "mainstream" – European-American, middle-class English as a primary language. This includes English Learners (ELs) of various ages,

quickly becoming one of the largest non-mainstream demographics in the educational landscape. In 2009, 21% of 5- to 17-year-olds in the United States (or 11.2 million) spoke a language other than English at home (National Center for Education Statistics [NCES], 2011). As changing immigration patterns bring these learners into public schools and institutions, educators, administrators and politicians are unprepared, and conservative forces continue to fight against change. The result is that NDLB learners, particularly those marked as learners of English as a second language are treated as deficient, and receive limited and watered down access to curriculum in schools (Genesee, Lindholm-Leary, Saunders & Christian, 2005; Lee, 1999; Callahan, 2005; Buxton, 1998).

In response to such inequities, scholars have called for exploration of "multiple ways of knowing and doing science that are reflective of the social, historical, and political context in which science has been constructed and in which students learn that science" (Barton, 1998, p. 4). Such research needs to be aware of students' diverse backgrounds without essentializing them[22] (Lemke, 2001) and create

---

learners who are English Proficient and multilingual, and learners who speak English in a way that is not recognized in schools as being "correct."

[22] Essentializing refers to the attribution of natural, shared characteristics, often implicitly biological, to members of specific culturally defined groups (gender, ethnic, sexual-orientation,

"expanded opportunities for students to find a place for themselves in this world as legitimate peripheral[23] participants" (Bouillion & Gomez, 2001). My own work follows this line of inquiry by exploring the activity of students from non-dominant cultural and linguistic backgrounds in a community college classroom, with the goal of informing the design of educational tools that are more accessible to a broader range of ways of knowing and doing science.

Culturally and Linguistically Diverse Learners and Cosmology

Cosmology is a cutting edge field with a proven potential for catching people's attention (see introduction), but like other science fields, it has traditionally been dominated by European-American males. Although there is a large body of research on various aspects of equity in the science classroom, almost no research exists on equity in cosmology education, or even astronomy for that matter. Astronomy and cosmology have been de-emphasized in the national and state content standards on which K-12 standardized assessments are based (Palen & Procter 2006),

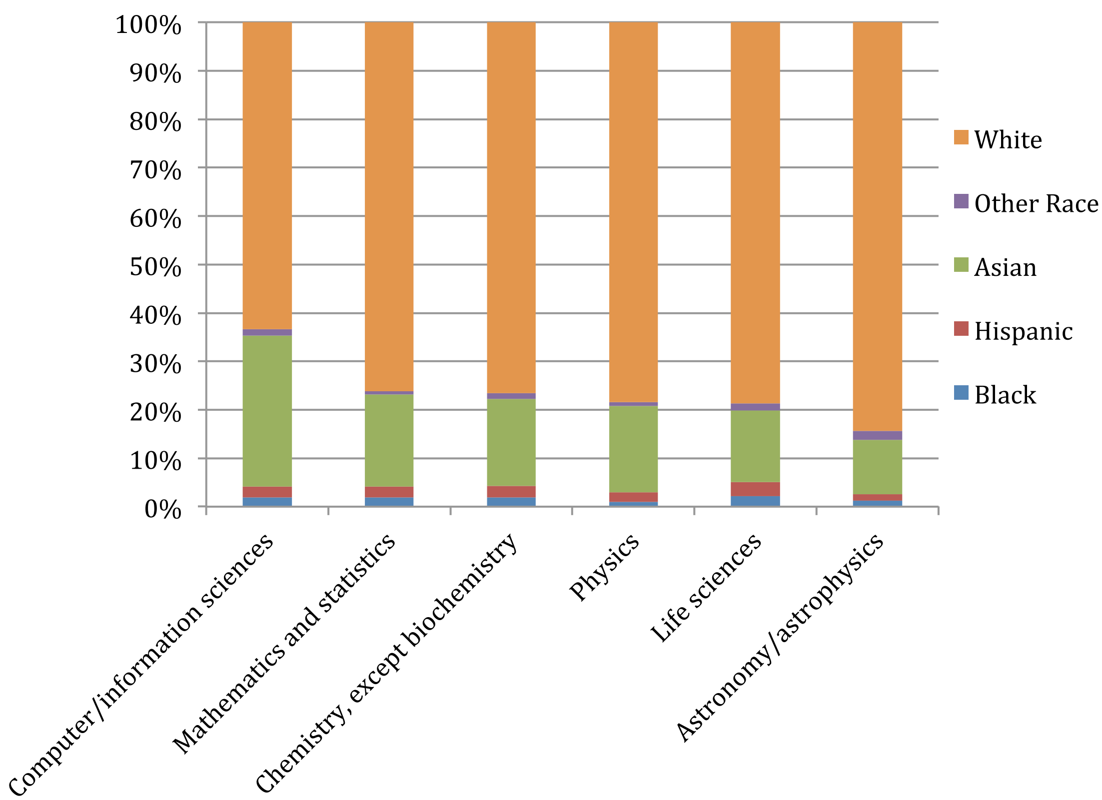
---

socioeconomic, linguistic, etc). Essentializing can result in thinking, speaking and acting in ways that promote stereotypical and inaccurate interpretations of individual differences.

[23] The use of the term "peripheral" here does not imply exclusion, but rather the evolution of inclusion as a participant becomes more and more involved in various practices associated with a community (Lave & Wenger, 1991)

making it even less likely that culturally and linguistically diverse learners in “teach-to-the-test” classrooms will be exposed to astronomy and cosmology content. This is reflected in the statistics on who is receiving degrees in astronomy, where the gap between mainstream and non-mainstream learners in higher education is even larger than that in other natural sciences; a significantly smaller percentage of doctorates in astronomy/astrophysics are conferred on non-white students than in computer science, math, chemistry, physics or life sciences (National Science Foundation [NSF], 2006), as shown in Figure 11 (National Science Board [NSB], 2006).

Figure 11. Science doctorates by field of study and race/ethnicity in 2006 (National Science Board, 2006)



More pressing than closing this statistical gap, providing access to cosmology, a complex and rigorous science content area, could open pathways to success for diverse learners in all post-secondary science (Mosqueda, Lyon, Buck & Maldonado, in press) through inculcation in the language and tools of science (Ash, 2003). This is particularly important for learners from non-dominant linguistic backgrounds, for whom acquiring "science talk" (Lemke, 1990) can be tantamount to a new language, characterized by its own vocabulary and style of talk (Shaw, 1997; Stoddart et al, 2002, Gibbons, 2002, Lemke, 2011; Shaw, Bunch & Geaney, 2010). Nor is the language of science homogenous across domains; for example the definition of a "metal" is very different for a chemist than it is for an astronomer, and neither definition matches that used in colloquial conversation.

Thus science learners who are also NDLB are being asked to learn not only English, but English science talk, essentially a third kind of literacy (Lemke, 1991). On top of this, students who are put into English as a Second Language (ESL) tracks are getting access to watered-down academic content and are treated as deficient (Buxton, 1998; Callahan, 2005; Oakes et al. 1990). Pease-Alvarez and Hakuta (1992) synthesize the research on English Learners this way: "Don't worry about English; they are all learning it; instead, worry about the instructional content; if you are going to worry about language, worry about the lost potential in the attrition of the native language, for all of the languages of the world are represented in this country" (p 6). But instead, NDLB students are not getting access to any science content until they are "mainstreamed," at which point they are behind (Callahan, 2005; Buxton, 1998).

In fact, tracking and course-taking are more significant indicators of achievement than is English proficiency (Callahan, 2005; Mosqueada, 2010). NDLB students in classrooms where the learning was both challenging and meaningful were more successful than their peers in more traditional ESL classrooms (Genesee at al., 2005).

Unfortunately most science classes focus on teaching science knowledge without emphasizing literacy and science language (academic discourse, social discourse, cultural understanding) (Lee & Fradd, 1998). Educators need to be aware of diverse experiences and patterns of communication (Moschkovich, 2011; Fradd & Lee, 1999; Solano-Flores & Nelson-Barber, 2001) without essentializing cultural traits, encouraging multiple ways of communicating and demonstrating knowledge, rather than silencing students who do not communicate in a mainstream ways. Effective teaching for these learners requires research-based tools that provide direct access to science content while supporting the development of both English and science literacy.

Methodology: Using Visualizations to Support Learners' Competencies

Dynamic scientific visualizations could be particularly useful tools for classrooms with non-dominant linguistic background (NDLB) students, as they provide access to content without high linguistic demand. This does not exclude high cognitive demand, and visualizations can be very challenging and productive learning tools. We know that such simulations and visualizations can serve to help students generate their own mental images, and deepen their engagement in conversations around the content (Wu, Krajcik, & Soloway, 2001). While they are often accompanied by narration, an enormous amount of basic information about system dynamics and structure can be coded in the imagery of the simulation alone (Evagorou, 2009). Visualizations can take advantage of “the power of alternative formats in communicating ideas” (Lee & Fradd, 1998, p 17). In figuring out the science content, NDLB students can use their native language to have conversations about things that they have seen, without being constrained by their lack of familiarity with the concepts and vocabulary. Thus the content does not require immediate mediation through specific vocabulary; rather, vocabulary can be introduced which is mediated by the content, and which can eventually mediate interactions with that content. That makes visualizations a rich jumping off point for hybrid classroom discussions that can introduce students to new ways of talking and thinking about the Universe. Visualizations are flexible learning tools that can bring the hidden aspects of the Universe into students’ experience, and inculcate students into some of the tools of science.

Access to scientific tools like visualizations that are designed to be inclusive of diverse ways of knowing and doing science is a critical condition for the success of traditionally under-represented students. Yet these visualizations are typically made by teams of scientists, and then disseminated to learning institutions often without being evaluated. In chapter one I showed the importance of the way that we present visualizations in terms of cues like color that can mediate learners’ interpretation. Well-designed learning tools in science educational settings require an ongoing cycle of research and implementation. But too often, such a cycle serves to perpetuate the status quo: researchers sample a mainstream demographic because they are most visible in classrooms and informal education settings (e.g. Baxter, 1989; Schneps et al., 1988; Plummer, 2009; Lee et al., 2014), and based on this kind of research mainstream learners will be better served, perhaps at the detriment of other, less visible learners (Darder, 1991; Rodriguez, 2004; Moschkovich, 2002). Thus it is vital that we study the ways in which learners from diverse cultural and linguistic backgrounds are *learning* using these visualizations (Brown, 2004; Ash, 2003).

But before we begin such an investigation, we need to define learning. In science education, learning has traditionally been framed as a process of overcoming misconceptions, and replacing them with scientific knowledge, as described in detail in the introduction. The vast majority of astronomy education literature takes this perspective (e.g. Schneps, 1989; Vosniadou & Brewer, 1992; Prather, Slater, & Offerdahl, 2002), known as conceptual change theory (Strike & Posner, 1985). But the conceptual change framework is not always fair to the learner, whose prior knowledge is treated as a barrier to learning, rather than a resource (Lemke, 2001; Warren et al., 2005; Lee, 1999). Sociocultural theory suggests that learner's ideas are not misconceptions that need to be replaced, but logical and constructive and situated ways of looking at the world that can be used productively in learning (Warren et al., 2005). My research comes from such a perspective, which sees learning as a complex, situated, social process (Vygotsky, 1978; Lave & Wenger, 1991). While conceptual change frames everyday and scientific knowledge as discontinuous, science education researchers with a sociocultural lens see the learning of science as a continuous process, and "everyday knowledge" not as a barrier, but as a potential resource for learning (Warren et al., 2005; Lee 1999). Research focusing on the academic activity of culturally and linguistically diverse learners can serve not to serve these students better in the classroom, but can potentially break down pervasive discourses that frame such students as deficient (Moschkovich, 2013). According to Moschkovich (2006), "If we do not focus on the mathematical activity, then it may seem that bilingual learners do not engage in mathematical activity, and we may thus be contributing further to framing these learners as deficient. It is crucial to uncover, bring out, describe, and analyze the mathematics that bilingual learners are doing and that they are capable of doing" (p 5). Similarly in science, more research is needed that reveals what culturally and linguistically diverse students are capable of doing, as opposed to what they cannot do (Warren et al., 2005).

Thus I aim to move cosmology education research further from the tradition of uncovering learners' incompetence, toward uncovering learners' competence, and "exploring ways in which such competence can be supported to promote development of robust understanding of the physical world" (Warren et al., 2005, p 122). As such, I do not assess the scientific thinking of my students based on their articulation of the "correct" answer, a form of assessment aligned with outdated banking models of learning that rely on fragmented vocabulary memorization. Rather, I use the framework of "cosmological literacy." I defined cosmological literacy in the introduction as proficiency in the concepts and practices required to understand the scientific Universe on a cosmological scale, which I divided into four facets: gravity, organization, the invisible and the visible, and scale. These facets emphasize core concepts, interactions, and patterns over the memorization of individual components, which aligns well with the potential of visualizations to present dynamic and complex systems holistically. Hogan and Fisherkeller (1996) suggest that "such a perspective reveals that students' scientific thinking processes can be strong even when their ideas and assumptions are scientifically naive" (942). Thus analyzing how students' collaborative activity is mediated by concepts and practices associated with cosmological literacy can reveal scientific thinking without getting bogged down in specific pieces of fragmented knowledge. I define the construct of cosmological sense-making as engagement in such collaborative activity.[24] This allows my research questions, below, to focus on how visualizations are supporting/not supporting learners' competencies, rather than on what students are doing wrong:

---

[24] My use of sense-making is most closely aligned with that of Warren et al. (2001), who define scientific sense-making as "a varied complex of resources, including practices of argumentation and embodied imagining, the generative power of everyday experience, and the role of informal language in meaning making" (p 532).

1) How do cosmology visualizations support cosmological sense-making for diverse students?
    a. What concepts and practices associated with cosmological literacy emerge when community college students are making sense of visualizations while engaged in object-oriented activity in small groups?
    b. What strategies are employed by diverse learners in a community college classroom to make sense of cosmology visualizations?

Answering these questions will suggest new ways to design and use visualizations in classrooms that better fit the activity of non-dominant learners who have been consistently left out of STEM in higher education.

Methods

Research Context: Community College

As cosmology content is rarely encountered in high school I have chosen to focus on learning in community college. A high percentage of culturally and linguistically diverse post-secondary students in California attend community college. These are primarily Latino/Latina NDLB students who are generally not being exposed to cosmology content in other places. Expanding access to cosmology in community college through these visualizations could open up pathways to success in post-graduate science for these students.

This research was conducted at a satellite branch of a central California community college. This branch is located in a small farm town with about 12,000 residents, and an 87.5% Hispanic population. Less than a third of the city's population speaks English as a first language at home. This high concentration of learners from non-dominant cultural and linguistic backgrounds is representative of the changing demographics of California's community college classrooms. However, it is important to note that cultural traits are not inscribed within individuals (Gutierrez & Rogoff, 2003), and the conclusions drawn from this study cannot be generalized to all Latino/Latina, Spanish- speaking learners, but should be used to *broaden* our understanding of how these visualizations can be used to support learning. Any study that frames itself in terms of race, class, gender, culture of language should be explicit about the limitations of such notions, all of which "owe their origins and historical prominence to explicitly political rather than scientific agendas," and "represent potentially misleading and harmful oversimplifications of the complexity of human similarities and differences" (Lemke, 2001).

Participants were recruited from a community college course in introductory astronomy, designed and taught by me. I worked with 41 participants, organized into 15 groups of 2-4. Every participant in this study was bilingual or multilingual, speaking both English and Spanish to varying degrees. Several of these students attended class with their families, resulting in a mixed-age sample ranging from middle school students to grandparents. Participants were mostly women, with only seven males choosing to participate.[25] With students' permission, I recorded their activity within friend and family groups as they interacted with the one of three cosmology visualizations, which are described in Appendix B. For students who felt uncomfortable with the English narration, the visualization was played a second time, with Spanish translation. Rough transcription was done by outside coders, and then based on these transcripts I completed a fine transcription. During the fine transcription process, data was double checked for accuracy, and gestures and drawing activity were preserved whenever possible.[26] Activity and interviews in Spanish were translated for the purpose of data analysis, while preserving how first and second languages were used as resources for learning in the context.[27] I did all

---

[25] This is at least in part a reflection of the gender makeup of my class, which is majority female.

[26] Bilingual students' use of gestures to convey meaning has been documented as important for understanding their meaning making (e.g. Moschkovich, 2002)

[27] According to Moschkovich (2006), it is essential to preserve the use of language in the discourse of bilingual speakers. She suggests that the researcher focus "on the ways in which individuals who use more than one language operate along a continuum of modes. Thus, depending on whether they are speaking to a monolingual or another bilingual, bilinguals make use of one language, the other language, or the two together as they move along a continuum from monolingual to bilingual modes."

translation, in consultation with native Spanish speakers. The original Spanish transcription is always presented in the data alongside the translation. Drawings, video and field notes were preserved for all 15 groups for the purposes of analysis, however due to poor audio and the logistics of fully transcribing/translating majority-Spanish data, only ten groups were chosen for transcription and rigorous coding. These ten groups were comprised of a total of 29 participants.

Introduction of The Improvable Object

Because sociocultural theory tells us that learning is primarily an active, social process, and that knowledge is socially constructed; and because visualizations are primarily a passive, individual medium (Small & Plummer, 2010), I have developed an activity that encourages students to work collaboratively, and engage actively toward the construction of an "improvable object" (Wells, 1999; 2002). An improvable object can be a symbolic artifact, a document, or a material artifact. Sociocultural theory tells us that human activity tends to be motivated by participation in collaborative practices in which something useful is being produced (Lave & Wenger, 1991; Engeström, 2010). The improvable object serves this purpose in educational settings, providing something on which subjects can collaborate to produce something useful.

Traditional classroom patterns of discourse, a grammar that originated from the banking model of learning, can suppress peer-peer learning opportunities, and obfuscate the object of student activity (Wells, 1999). Without a clear object, students fall into patterns of repetitive actions toward short-term goals (e.g. get the multiplication problems right, copy the sentence over and over). In Leont'ev's famous example of "the hunt" (see introduction), this would be like asking the hunter to chase the prey in a specific direction, without establishing the object of capturing it for dinner. Why would the hunter be motivated to participate? This can result in students that appear "unmotivated," to participate in the learning of de-contextualized "facts" about the natural word.

To avoid falling into the trap of the banking model, we can structure educational activity in such a way as to allow activity systems to play out naturally, rather than streamlining the transmission of information from teacher to student. According to Wells (1999), supporting object-oriented activity in the classroom encourages "progressive knowledge building," in which students "not only develop their understanding about particular topics but also master the modes of meaning making and genres of discourse that mediate knowing in the different disciplines" (p 16). In other words, it establishes domain literacy, rather than the random acquisition of facts within the content of the domain.

Wells (1999) identifies what he calls the improvable object as the focus of activity oriented toward progressive knowledge building. Improvable objects create "opportunities for students to bring their experiences and ideas to the topics being investigated, while at the same time ensuring that the ensuing conversations contribute to their curricular objects-in-view." Wells (1999) identifies the following six aspects of improvable objects:

1. participants work collaboratively to improve them
2. they involve a real problem that requires discussion
3. they provides a means to an end, rather than being an end in themselves
4. they act as a focus for the application of experience
5. they act as a focus for the application of information
6. they inspire and focus a progressive discourse.

Wells explains that the improvable object serves as a focus for activity, whereby "[t]he attempt to find a way of moving toward the goal or of creating and making improvements to the product provides a joint focus for effort and attention and stretches all concerned to 'go beyond themselves' in both skill and understanding." This movement "beyond themselves" is an operationalisation of Vygotsky's zone of proximal development (ZPD). When the activity system moves through the ZPD, we can say that scaffolding is taking place. I use this definition of scaffolding below to highlight and segment data where learning is taking place.

Data Collection and Analysis

My primary data source was video of each group of students engaged in activity after seeing a cosmology visualization (described in Appendix B). To introduce an improvable object into the activity, I provided participants with a piece of paper and markers, with instructions to work collaboratively, and draw what they "learned" in the visualization. The word "learned" is vague, and was not elaborated on. It was chosen deliberately to provide a point of discussion among participants to encourage dialogue around the content of the visualization. There is a precedent for using drawings in the literature, for example such drawings have been used to investigate children's ideas about the solar system (e.g. Vosniadou & Brewer, 1992; Trundle, Atwood, & Christopher, 2006), families experience of museums (Crain, 2010), and students' conceptions about cosmology (Coble et al., 2010). In addition, this activity allows me to capture the participants engaging in a variety of natural communication modes (talk, gesture, symbol). Emphasizing and valuing alternative modes of communication is a strategy for effective assessment of diverse learners (Moschkovich, 2007) and expands the ways in which participants can express their competences (Warren et al., 2001).

This chapter is framed by second generation activity theory: thus the activity system is my unit of analysis and I am not concerned with the actions of a single individual, but how those actions taken together with the actions of other individuals, mediated by tools, constitute learning activity (Engeström, 2010). Using video allowed me to capture the participants engaging in a variety of natural communication modes (talk, gesture, symbol). The coding scheme discussed below is applicable to the activity of students during the drawing phase, not to the interview afterward. Interview data was used to contextualize and expand on themes that came up in the drawing.

Macro-level analysis: Using scaffolding scenes to focus on learning

Sociocultural theory tells us that conceptions are situated (Lave & Wenger, 1991), and that knowledge is socially constructed (Vygotsky, 1978). While it is important to note that this does not mean that learning always happens in groups, it does highlight the important role that collaborative activity plays in the construction of new knowledge. To understand learning in small groups such as those I propose studying here, I frame the process of collaborative knowledge construction within cultural historical activity theory (CHAT). CHAT grew from the work of Vygotsky (1978) in Russia, and is primarily associated with his colleagues Leont'ev and Luria (Wertsch, 1981). Activity theory looks at all human behavior in terms of activity systems, cooperative human interactions in which activity is mediated by tools and artifacts, and oriented toward and object, or goal (Engestrom, 1987; Nardi, 1996). Within this framework, the visualization takes on a role beyond that of passive transmitter of knowledge. From this perspective, learning can be defined as changing participation (Lave & Wenger, 1991) in activity embedded in a complex network of dynamic activity systems. If we seek to understand how learning is supported by cosmology visualizations, we need to expand the uni-directional visualization-learner dyad, to see both learners and visualization as dynamic parts of an activity system where new forms of participation are taking place.

Educators, parents and politicians are particularly concerned with the question of "effectiveness." Is a learning tool doing its job? When learners use the learning tool, are they *learning*? The focus on effectiveness should not be surprising given the limited availability of funds for advanced learning technologies, and the current educational climate of accountability and testing. From a CCT point of view, the tool is effective (learners are learning) if it encourages students to reproduce the right answers, rather than the wrong ones. From a CHAT point of view, the unit of analysis is larger than the single individual, so such an analysis would be overly simplistic. From a CHAT perspective, it is not interesting to ask "are learners learning from the visualization?" without specifying an activity for the visualization to mediate. In other words, while it is perfectly legitimate to ask how a visualization mediates student activity oriented toward completing a particular standardized test, these results are not necessarily applicable to the ways in which the students may discuss the visualization with her peers, or apply that visualization to interpreting the dynamics of a different kind of scientific system. Thus, I do not find it useful to define learning along the lines of performance on a standardized assessment. Instead, I use the concept of scaffolding, an operationalization of Vygotsky's ZPD, to conceptualize an activity system in which learning is taking place.

The metaphor of scaffolding is an old one, first appearing in educational scholarship in a 1976 paper by Wood, Bruner and Ross describing how adults served as tutors for children learning to solve a problem involving the construction of a pyramid out of blocks. The increasing use of scaffolding in education scholarship throughout the next decade reflected a field-wide shift in the United States away from the Piagetian framework (Piaget & Inhelder, 1969) of individual learner as the "proximal locus of development" (Cole and Wertsch, 1996, p. 250) toward the sociocultural point of view. After the publication of Vygotsky's *Mind in Society* in the United States in 1978, scaffolding began to take on a new meaning in light of changing views on how learning takes place. Through this lens, scaffolding has come to describe the process of working within the "zone of proximal development" (ZPD), which Vygotsky (1978) defined as "the distance between the actual developmental level as determined by problem solving and the level of potential development as determined through problem solving under adult guidance or in collaboration with more capable peers (1978, p 86)." Thus if someone more capable helps a child achieve more than that child would have been able to on her own, the child is working in the ZPD.

Researchers in the learning sciences conceptualize the role of artifacts, particularly technology, centrally within the scaffolding process. In a special issue of *The Journal of the Learning Sciences* published in 2004, Tabak (2004) posits that a "synergy" between teachers, technology and tools can strengthen the scaffolding experience. She argues that "software supports and teacher coaching…address the same learning need and interact with each other to produce a robust form of support." This is in stark contrast to the original definition of a scaffold as an adult supporting the learning of a child. Taking on such an expanded view of what constitutes a scaffold means that a single learning setting, like for example a museum exhibit, could have dozens of potential scaffolds for learning (e.g. signs, interactives, toys, visualizations). These artifacts therefore serve both to mediate scaffolding activity, and as objects of the activity.

Sherin, Reiser and Edelson (2004) argue that the new trend of using scaffolding by "researchers in the learning sciences to describe features and functions of technological artifacts, especially those of educational software" requires a new framework for analyzing the effects of the process. They do not see scaffolds as “features of artifacts or situations, nor is ‘scaffolding’ something that may be occurring (or not) in a given situation that we observe” (Sherin, Reiser & Edelson, 2004, p. 387), rather the emphasis is put on the interaction itself. Although the authors do not specifically refer to CHAT, this is essentially refocusing the emphasis of research onto the activity system, rather than on individual artifacts or subjects.

The metaphor of scaffolding acquires new depth and dynamic by incorporating elements of CHAT. Theorizing from this perspective requires a view of scaffolding that is multi-directional and “co-active” (Mascolo, 2005), occurring when “elements of the person-environment system beyond the direct control of an individual actor direct or channelize the construction of action in novel and unanticipated ways (Mascolo, 2005, 187).” There is an emphasis here on ambiguity and surprise, both essential characteristics of an object-oriented activity system (Engeström, 2010). This view centralizes the fact that responsibility for the scaffolding is distributed equally within the system, and that knowledge is co-constructed. The co-active scaffolding model imagines the ZPD not as a personal space carried and cared for by the individual attached to it, but rather as a shared space in constant flux, within which subjects in an activity system co-construct meaning and knowledge (Mascolo, 2005; Granott, 2005). Engeström (1987) defines this new ZPD as “the distance between the present, everyday actions of the individuals and the historically new form of the societal activity that can be collectively generated” (pg 174). When an activity system moves through the collective ZPD, this is scaffolding. Thus a tools that is functioning as a successful scaffold will be part of an activity system in which the activity is more than the sum of individual actions. Such a system will use cosmology visualizations in unexpected ways, and grow from internal and external contradiction and conflict (Engeström, 2010) to promote novel forms of activity.

In order to seek scaffolding explicitly, activity can be segmented into "scaffolding scenes… an enactment of mediated action by people toward some particular goal or outcome" (Mai & Ash, 2013). Such scenes have been used to analyze family activity at museums. Mai & Ash (2013) define a scaffolding scene as follows:

> Any interaction or exchange between at least two people that involves guidance, leading questions or comments, and/or direct teaching...They include identifiable exchanges involving at least two people that include at least one turn. An exchange is defined as an initiation of talk or gesture that solicits a response in the form of talk or gesture. Such scaffolding is designed to fade over time, as learners have advanced in the collective ZPD (p 67).

Some of the processes traditionally considered indicators of scaffolding (from Wood, Bruner & Ross, 1976) and used to identify scaffolding scenes in this study scenes include:

- *Recruitment and direction maintenance*: Orienting the learner's attention to the task, and directing her/him to achieve a goal.
- *Simplifying the task*: Simplifying the situation in a way that the learner can handle the components of the process, and highlighting what is important.

- *Controlling frustrating and risk of failure:* Reassuring and affirming choices and actions, correcting errors. This can include "filling in" gaps in the learners' knowledge.
- *Demonstration:* Modeling completion of the task.

A scaffolding scene will include one or more of these processes. In the next section, I present and describe a scaffolding scene to illustrate how such processes appear in the data. I define the boundaries of the scaffolding scene by identifying short-term yet object-oriented actions within the activity, such as deciding the color of a component, or labelling the timeline of the drawing.

Breaking up continuous activity into scaffolding scenes serves to segment data in a way that highlights learning activity, without isolating individual actions from the context of human activity. Scaffolding scenes that fit these criteria, and were related to the visualizations (rather than side discussions regarding sharing, drawing materials, etc.) were transcribed for coding. On average, each video of a group activity from the data included 2-3 identifiable and transcribable scaffolding scenes. Approximately 10% of data was lost due to poor audio quality.

Example from the Data: The Gonzalez Family

Through negotiating content and action, the drawing activity provided a space where students were scaffolding each other in their collective ZPD, pushing each other to notice and describe things they may not have alone. In this section I use a scaffolding scene from the data to illustrate both the potential of visualizations as scaffolds, and the usefulness of a drawing activity in providing a space for students to engage in scaffolding, functioning as an improvable object. The bounding action in this scene, constantly being negotiated and renegotiated by the participants, is making sense of the appearance of dust around the galaxies in the visualization.

Esmeralda[28] and her children were all taking the class together. Her two sons, Steven (16) and Joseph (14) were getting high school credit, and her daughter Sara (12) was taking it for fun. In the scaffolding scene below, the Gonzalez family negotiate and figure out the visualization they have just seen of two galaxies merging narrated by Joel Primack (see Appendix B, Visualization 1).

JOSEPH: [Adding big dots by hitting the pen against the paper]
ESMERALDA: [Motions toward the corner]
SARA: Try not to <dab it in there> <????> [makes a motion of using the pen with her hand]
JOSEPH: [Puts yellow pen away]
ESMERALDA: [Adds more blue dots]
JOSEPH: Those don't really have form..they're just like...
ESMERALDA: Mmmm, cuz then this one [points with brown pen, begins adding dots to corner] this one had like a atmosphere...right?

[28] All names in this dissertation are pseudonyms to protect the anonymity of participants, unless otherwise stated

JOSEPH: Mhhmm
STEPHEN: These are galaxies, galaxies don't have an atmosphere
ESMERALDA: No, but like, you said this one's got filler
STEPHEN: Yeah, dust
ESMERALDA: Here you go [she puts the blue pen down between Stephen and Sara, implying it should be picked up...it is not yet]
STEPHEN: The dust was brown
ESMERALDA: Okay...you do that part

In this example we see Joseph drawing one of the galaxies with help of his family. Sara guides her brother as he draws to resemble better what she remembers. Joseph states that the galaxies don't "have form," and Esmeralda introduce the concept of the "atmosphere," a word she is using as a place holder for something she has seen surrounding one of the galaxies. She adds blue dots to represent this "atmosphere," and Joseph agrees. Stephen reminds them that "galaxies don't have atmospheres," to which Esmeralda goes back to the everyday concept of a "filler" that Stephen had used to describe dust in an earlier scaffolding scene. She uses his understanding of dust to reframe what she has seen. Stephen re-introduces the scientific vocabulary word dust from the narration, and describes it as "brown," to which Esmeralda suggests that he add the dust to the drawing. From the start to the end of the scene we see the family's discussion of the galaxy move from "not having form," to having an "atmosphere" to being surrounded by a wispy mass of "dust," a more scientific explanation. Stephen, as the oldest son and highest achieving student, takes on the role of providing scientific vocabulary for his mother and siblings, without stepping in and performing the task on his own, a form of scaffolding known as *controlling frustration* (Wood, Bruner & Ross, 1976). Esmeralda takes on the role of encouraging and directing participation in the activity for her kids, a form of *recruitment and direction maintenance* (Wood, Bruner & Ross, 1976). The family has moved through their collective ZPD, scaffolding one another.

This episode is an example of co-active scaffolding, an actualization of new forms of human activity (Wells & Claxton, 2008) that would not have been possible for an isolated individual. I break participant activity into scaffolding scenes in order to highlight these new forms of participation in my analysis, places where "learning" is taking place, and in order to segment larger activity into smaller units of activity without losing context.

Micro-level analysis: Utterances

Within scaffolding scenes, I first coded interview data in chunks bounded by relevant "utterances" (Bakhtin, 1986). Bakhtin emphasized the importance of looking at speech in terms of the utterances, rather than linguistic form, claiming it to be the "real unit of speech communication" (Wertsch, 1991, p 50). This distinction is very important, because by moving away from the grammatically defined "sentence," we move away from the passive assumption that any unit of speech can be understood fully on its own. The utterance, on the other hand, has borders defined by a change of speaker, therefore implicitly contextualizing the unit of speech within a larger interaction. By analyzing utterances, I am working with the inherent dialogic nature of speech, rather than attempting to apply grammatical boundaries. For an utterance to be coded, it needs to be participant dialogue, and regarding the drawing in some way, or astronomy content, not discussion of participant details, background, etc. This is in part to simplify coding and to keep participants as anonymous as possible. In addition, gestures related to either science content or the action of drawing were also coded as utterances, to preserve their importance as modes of communication within the activity.

My intention in such micro coding within the scaffolding scene is to identify the illocutionary force (Austin, 1962) of the utterance (or series of utterances). Within the co-active person-environment system I described above, I see an utterance as not just words, but human action, which realizes the purpose of the speaker in deciding to speak in the first place (Wells, 1981). This purpose can generally be classified as either give information, give action, solicit information, solicit action, acknowledge information, or acknowledge action. This required only two levels of coding: give/solicit, and information/action/acknowledge. I used these coding categories to distinguish dialogue that negotiated science content from the visualization (coded as give or solicit information), as opposed to dialogue that negotiated how to represent the visualization on paper (coded as give or solicit action). In order to maintain this distinction, which was more relevant to my analysis, information about action was coded as action. For example, if a participant asks "should we draw this here?" the utterance was coded as solicit action, because the participant is asking a question related to the action of drawing, not to the information in the visualization. Dialogue or gesture not coded as utterances were preserved within the scaffolding scene in order to maintain the overall integrity of the activity in analysis.

Coding for cosmological Sense-making

I have defined cosmological sense-making (CSM) as engaging in object-oriented learning activity mediated by concepts and practices associated with cosmological literacy. In other words, CSM provides a name for when students are using one or more of the four facets of cosmological literacy introduced earlier as they figure out the content of a visualization. Thus my coding rubric for CSM is based on manifestations through dialogic action (Wells, 1999) of one or more of the four facets of cosmological literacy. Within each facet I have broken down the various levels of sophistication with which a student might apply that concept or practice to mediate action, providing hierarchical CSM "indicators." The rubric for these CSM indicators is given in Table 6 below.

I coded for each indicator regardless of scientific accuracy. For example, if a student identifies "stars and galaxies" when the visualization was meant to indicate clusters of galaxies, the utterance was still coded as first-level identifying components (C1). Hogan and Fisherkeller (1996) justify such an analysis succinctly: "Teachers who encourage students to build and evaluate their own ideas must expect that there will be gaps and inaccuracies in students' conceptions...we suggest that tracing the elaboration of students' ideas, accurate or not, yields information about the quality of their reasoning processes... Such a perspective reveals that students' scientific thinking processes can be strong even when their ideas and assumptions are scientifically naive" (p 942). Thus such an analysis is sufficient to reveal scientific thinking. In addition, I aim to put the focus of my analysis on what students can do in order to inform new ways to support their competency, rather than putting the focus on what they don't know, as in traditional conceptual change research. Both the scaffolding scenes and the drawings were coded for cosmological sense-making.

Emergent Coding

Several additional codes emerged from analysis based on the specific activity of the participants, and were used to organize the data and reveal the strategies being employed by the participants to answer my third research question. These included:

1) Various types of visual analogies used by participants to give information: attributional (referring to aesthetic similarities/differences) or relational (referring to dynamic similarities/differences) (Gentner, 1989; Gentner & Markman, 1997).
2) The introduction of new scientific vocabulary versus the use of familiar vocabulary, including utterances that use a bit of both. This kind of discourse, which incorporates familiar, "everyday" talk with emerging "scientific" talk, is known as *hybrid* language (Lemke, 1991; Ash, 2008).

The use of analogy (both attributional and relational) and hybrid (scientific/everyday, Spanish/English) talk emerged from the data without my seeking them explicitly. Both are supported in the literature, which is presented below in the discussion section.

Table 6. Coding for indicators of cosmological sense-making.

Coding symbol	CSM indicators (cosmological literacy concepts/practices)
C	**System components and organization** – 1- Identifying important system components (example: "La otra que estaba aca") 2- Explicit labeling of stars, galaxies, dust and other cosmological bodies and systems (example: "that's a galaxy") 3- Description of component characteristics (example: "the dust was bornw"), Identification of how components are related to one another (example: "the filaments are made up of galaxies")
G	**Gravity** – 1- Describing the large scale movement of system components through space (example: "all the stars…y la otra {*the other*} are coming this way") 2- Identifying or describing dynamic relationships between components and between a component and the larger system (example: "Se alejo, so se vino pa' aca {*they move away from each other…it came over here*}") 3- Explicit reference to gravity as the motivating force (example: "It comes together because of the gravity")
D	**Invisible/Visible** – 1- Identifying invisible components, or labeling visible components of the model as invisible (example: "you can't see that in real life") 2- Identifying dark matter or dark energy (example: "those are dark matter, not stars") 3- Attributing system dynamics to hidden components, such as dark matter or dark energy (example: "the galaxies are inside the dark matter halos because of the mass")
S	**Scale –** 1- Identification of cycles or change over time (example: "this happens first, and this happens second") 2- Identification of deep time/scale (example: "this happens after billions of years" 3- Identification of the effects of deep time/scale on dynamics (example: "it takes too long for it to travel all the way across"

Results

My results can be summarized around three themes, each of which addresses a research question. The first theme is about the role of the drawing activity as an improvable object, the second is around cosmological sense-making, and the third is around strategies for discussing and negotiating the scientific content of the visualizations. In this section I will present my results, followed by several examples from the data to illustrate these themes.

Theme 1: Give/solicit action moves, indicating drawing activity, were almost always accompanied by or immediately following a give/solicit information move, indicating that they were explaining or describing something from the visualization. This suggests that the drawing activity was prompting participants to engage in activity oriented toward making sense of the visualization, functioning as an improvable object within the system.

Theme 2: Students demonstrated several CSM indicators in their activity, including a) the identification of system components like stars and galaxies, b) the identification of gravitational dynamics like the movement of galaxies through space, or the flow of stars in a galaxy collision, and c) the identification of cosmic timescales. See Table 7. Noticeably, only one participant mentioned gravity during the drawing activity in order to explain the dynamics of the visualization, despite every single group being able to explain gravity during the post-drawing interview. This was indicative of the dialogue of participants throughout the activity, which relied on pronouns, analogies and everyday language as placeholders for scientific vocabulary so that the conversation could focus on the dynamics of the system, as revealed in theme 3.

Theme 3: When negotiating content (coded as give or solicit information) students were referring to the system dynamics of the visualization using hybrid language (everyday/scientific, Spanish/English), even when the "correct" vocabulary eluded them. This included the use of analogy to describe unfamiliar aspects of the system using more familiar terms, such as relating gravity to magnets, or filamentary structure to the nervous system.

In Table 7 and Figures 12 and 13, I summarize the number of participant groups who manifested each cosmological literacy pattern, and the total number of times a pattern was coded. Clearly identifying components was the activity that students were engaged in most, primarily at level 2, meaning that they were assigning labels to various elements of the visualizations. Second most popular was identifying gravitational dynamics, both the dynamics of individual components, coded as G1, and dynamic gravitational relationships, coded as G2. Some groups also spent time making sense of the temporality of the visualization, particularly by organizing the visualizations into discrete time-steps, coded as S1.

Table 7. Coding summary for each indicator of cosmological sense-making.

Category	**Groups (n=11)**	**Total counts**
C 1	11	113
C2	11	128
C3	5	37
G1	6	106
G2	8	88
G3	1	2
D (1,2,3)	0	0
S1	7	26
S2	2	2

Figure 12. Bar graph of counts for each indicator of cosmological sense-making across the data set.

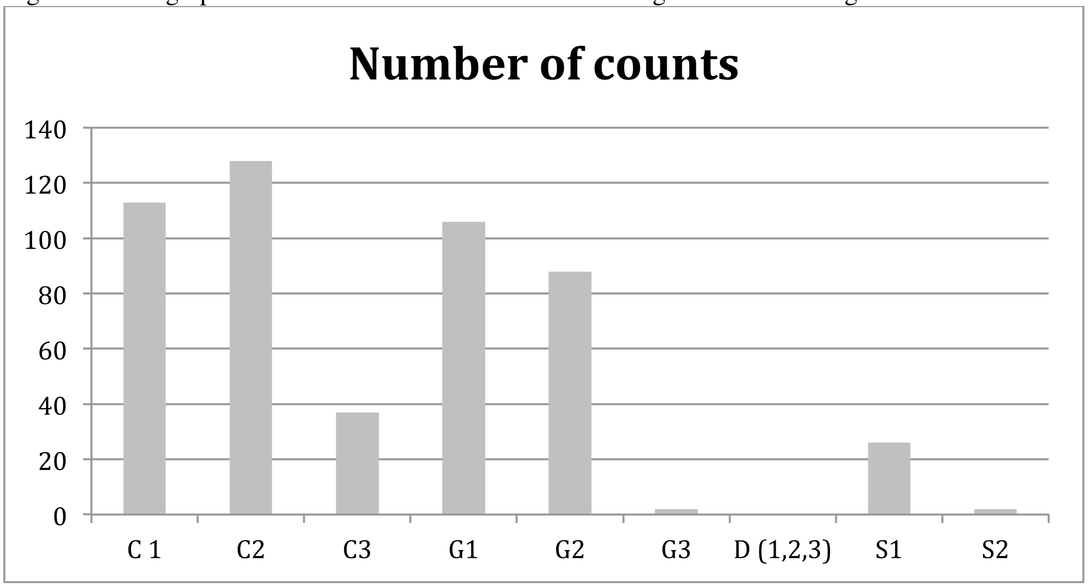
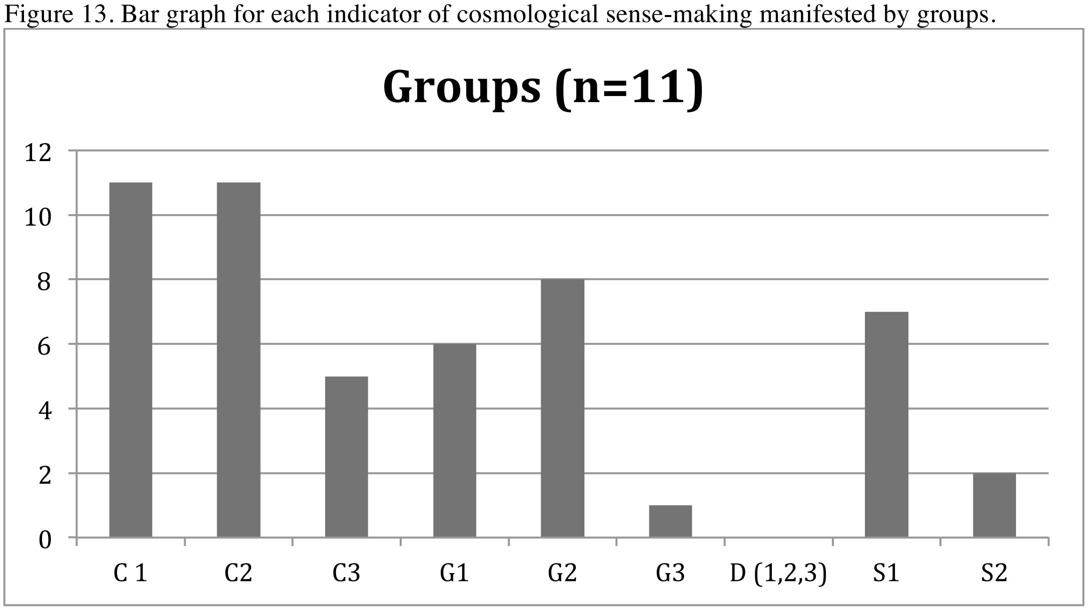


Figure 13. Bar graph for each indicator of cosmological sense-making manifested by groups.



In the table below, I summarize my findings across all ten transcribed interviews. In the left column are the participants. In the center column are the cosmological literacy indicators that they manifested in scaffolding scenes during the drawing activity. In the right column are the other strategies they employed during the drawing activity in order to make sense of the visualization.

Table 3.

Participants	Patterns associated with cosmological literacy	Other strategies
Mariana and Diana	C1, C2, G1, G2, S1	Hybrid language
Gonzalez Family	C1, C2, C3, G1, G2, S1, S2	Hybrid language, Attributional analogy
Juan, Michelle and Elena	C1, C2, C3, G2	Hybrid language, Attributional analogy
Maria and Yesmin	C1, C2, G2, S1	Hybrid language, Relational analogy
Alisandra and Lily	C1, C2, G1, G2, S1	Hybrid language, Attributional analogy
Jorge and Laura	C1, C2, C3	Hybrid language
Perez Family	C1, C2	Hybrid language
Eugenia, Esperanza and Ana	C1, C2, C3, G1, G2, G3, S1, S2	Hybrid language, Attributional analogy
Beatriz, Sonya and Paulina	C1, C2, C3, G1, G2, S1	Hybrid language, relational analogy
Flor and Xochitl	C1, C2, G1, G2, S1	Hybrid language
Manuel and Jose	C1, C2	

Example 1: Mariana and Diana use hybrid language to talk about dynamic relationships among components of the system

The first example from the data is a scene featuring Mariana and Diana, who are mother and daughter. Mariana and Diana illustrate well how the use of hybrid language facilitated their sense-making around the galaxy collisions visualization. Note their use of both Spanish and English, and scientific and everyday vocabulary in order to identify components of the system and their relationship to one another. The visualization they saw of a galaxy collision is summarized in Appendix B, Visualization 1. The first two rows make the coding explicit for clarity.

Utterance	Action	Coding
MARIANA: Y cuando las galaxias, y cuando se funden juntas, no? {*And when the galaxies, and when they fuse together, right?*}	Give, Info Solicit, Info	C2 - Identify components (galaxies), G2 – identify gravitational relationships (they fuse together)
DIANA: K the blue and the orange [grabs the blue and the orange pens, draws a red circle, and then blue dots around] and all the stars…y la otra {*the other*} are coming this way [she points at the bottom of the page]	Give, Action Give, Info	C1 - Identify components (stars), G1 - identify basic component dynamics related to gravity (coming this way)
MARIANA: La otra que estaba aca {*The*	Give, Info	C1

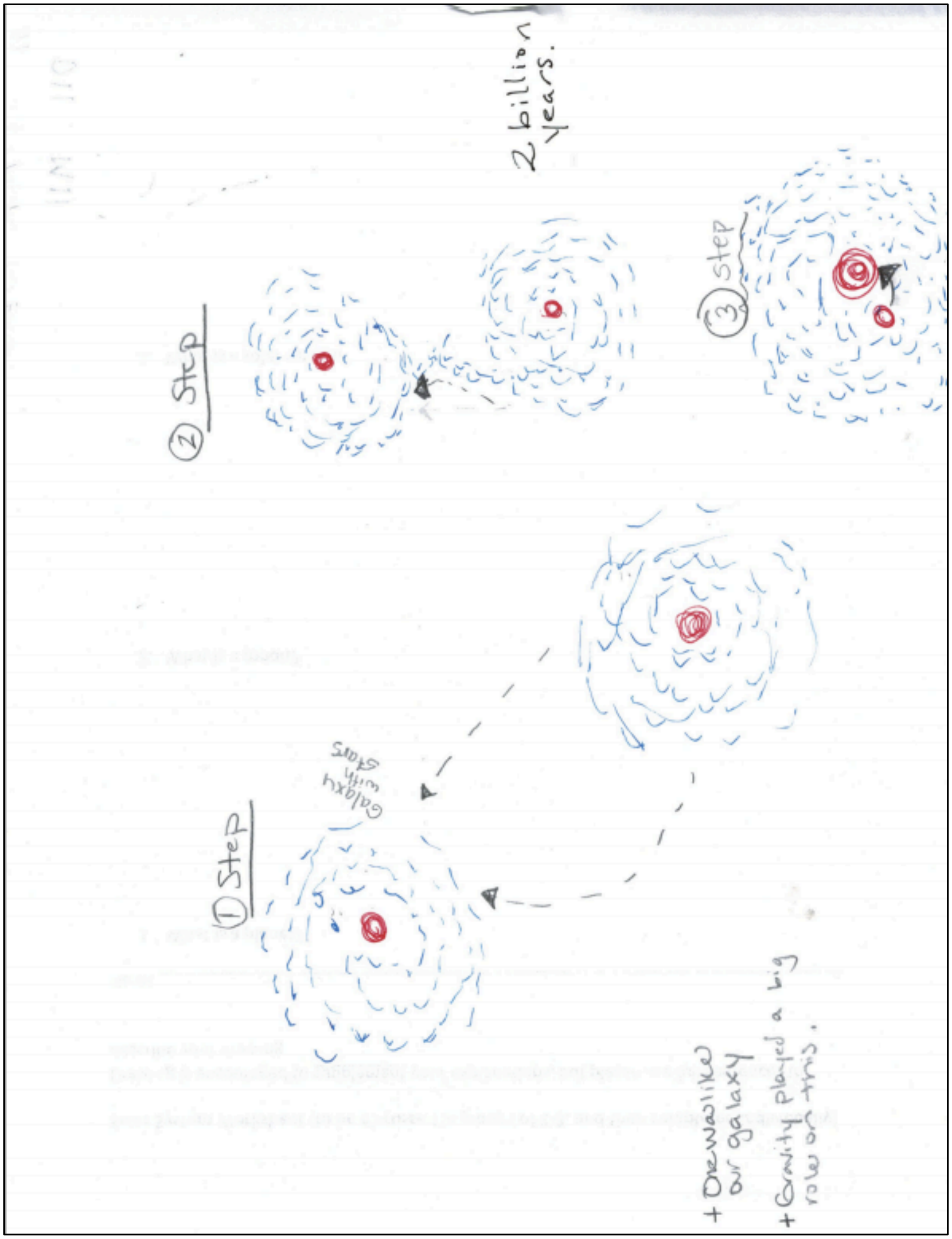
other one was over here} [picks up the red pen and draws another circle at the bottom of the page]	Give, Action	
DIANA: [Adds blue dots around the second red dot] And then…	Give, Action	
MARIANA: [picks up pencil] Estos se junten {*These come together*} [draws dashed line between galaxies] se juntaron {*They came together}*	Give, Info Give, Action	G2
DIANA: Asi, como… {*Like this}* [writes]	Give, Action	
MARIANA: Y esos paso no? {*And these pass, right?}* [draws a one with a circle around it] one step	Give, Info	G2,S1
DIANA: [writes "step" next to the 1]	Give, Action	
MARIANA: And the second one	Give, Info	S1
DIANA: [labels empty spot as step 2]	--	
MARIANA: Se alejo, so se vino pa' aca {*they move away from each other…it came over here*} [makes a new red dot, points around the red dot indicating that her daughter should put blue stars]	Give, Info	G2, G1
DIANA: [draws blue stars around third	Give, Action	C2, G2

dot} but then some of this one's stars [points to second galaxy] come over here [points to third galaxy]	Give, Info	
MARIANA: Mhm	Acknowledge, Action	
DIANA: So we have to draw this one kind of like, backing out, no?	Give, Action Solicit, Info	G1
MARIANA: si…so aqui? {*yes…so here?*}	Give, Action Solicit, Info	
DIANA: No, como aquí {*no like over here*}…okay and then some of it is coming over here	Give, Action Give Info	G1
MARIANA: Y los dos se volvio {*And they both go around*}	Give, Info	G2

Mariana and Diana use hybrid language, moving in and out of Spanish and English, and trying out different ways to describe the dynamics of the visualization that they saw. Take Mariana's first utterance, where she says that the galaxies fuse together. She uses the Spanish word "fundir" - to fuse, which was used in the translation of the narration of the visualization. Later, however, she uses everyday language to describe the same motion, saying that the galaxies "se juntaron" - came together. She is negotiating meaning here, using both everyday and scientific language to better put what she has seen in a context she understands. She also comments on the motion of the galaxies away from one another, a motion which is not described in the narration. This is an important and non-intuitive motion when understanding gravitational interaction. The expectation is often that two objects will move directly toward one another and merge immediately. Mariana has noticed the more complex dynamics of this interaction, without it having been explained to her explicitly. But she never uses the word gravity. This shows how important it is to listen to what students are saying, to "listen past English fluency" (Moschkovich, 2009; 2011), rather than relying on scientific vocabulary to establish what students are understanding.

Mariana and Diana's drawing is shown in Figure 14.

Figure 14. Mariana and Diana's drawing.



Example 2: Esmeralda, Steven, Joseph and Sara negotiate a galaxy collision

Esmeralda Gonzalez and three of her children were all taking the class together. They also saw the galaxy collision visualization (Appendix B, Visualization 1) Esmeralda's two sons, Steven (16) and Joseph (14) were getting high school credit, and her daughter Sara (12) was simply taking it for fun, with encouragement from her mother. Esmeralda is very focused on the logistics of who gets to draw what, in what color and where. Her children are less focused on these logistics, and more focused on what is being drawn, and how to illustrate the dynamics of the visualization. In this first scaffolding scene, the family is figuring out what to draw, and in particular how to represent a visualization that changes over time. This is an excellent example of how participants demonstrated the systems thinking patterns of identifying temporality. Led by Esmeralda, they decide to break the visualization into "stages," representing different points in time in the collision of the galaxies. Notice the way the older son (Steven) provides the scientific vocabulary for his mother's illustration (e.g. "those are stars") in order to identify system components.

Utterance	Action	Coding
ESMERALDA: When, do we do it at the different stages?	Solicit, Action	S1
JOSEPH: [Motions drawing a circle on the page]	Solicit, Action	
SARA: I don't know		
ESMERALDA: Right, cuz at the beginning...	Give, Info	
JOSEPH: Like do you want us to draw them...	Solicit, Action	

STEVEN: Well which one do you remember the most?	Solicit, Info	
JOSEPH: Like what?	Solicit, Info	
ESMERALDA: Well I remember there was one that had a lot of blue [making dots with blue marker on page]	Give, Info Give, Action	C1
STEVEN: Those were stars	Give, Info	C2
JOSEPH: I guess we're doing that then...	Acknowledge, Action	
ESMERALDA: Well we can do this one [points at blue dots she has made] and then we can do all the other stages [points at the page in a circle, marking different areas where different drawings can be made]	Solicit, Action	S1

The Gonzalez family spends several minutes finishing up this drawing, and discussing what colors to use for what, when their mother suggests that they move onto the next "stage" of the visualization. A major discussion point in this scene is the dust, a scientific vocabulary word introduced by the younger son. First the family discusses the color of the dust, and then they discuss how it is distributed, not as "spots," like the stars were, but as "filler." They modify the drawing in light of this discussion to reflect the nature of dust better.

Utterance	Action	Coding
ESMERALDA: Okay and the next phase [Picks up red marker from box, begins making dots in the same area]	Give, Action	S1
JOSEPH: I think...the dust was...	Give, Info	C2
JOSEPH: [Picks up brown pen from box]	--	

STEVEN: Yeah it wasn't red, the dust was brown	Give, Info	C3
JOSEPH: [Adds brown dots as M is adding red dots in the same area]	Give, Action	
ESMERALDA: [Pulls hand with red pen away from paper]	--	
SARA: Yeah that's why I got the brown	Give, Action	
JOSEPH: [Still putting brown dots on paper]	--	
SARA: [Puts both hands on paper to keep it from slipping]	--	
STEVEN: Dust more...is a filler	Give, Info	C3
ESMERALDA: <?>	--	
JOSEPH: [Pauses dot-drawing]	--	
STEVEN: So it wasn't so much spots	Solicit, Action	
ESMERALDA: [Takes brown pen offered by younger son]	--	
STEVEN: You know what I mean?	Solicit, Action	
ESMERALDA: [Slowly adding brown dots around outside of drawing] Yeah	Acknowledge, Action	
JOSEPH: <??> know what you mean	Acknowledge, Action	
ESMERALDA: [Dots start becoming dashes with brown pen]	Give, Action	

Note how the family negotiates the way in which the dust should be represented, based first on the more superficial color choice, and then later on the role that the dust plays within the system, and how this affects the way it should look. Esmeralda represents the dust as dots at first, until Steven gives information from the visualization that the dust was actually "filler." He then translates this information into proposed action, suggesting that it shouldn't be represented as "spots," an attributional analogy relating the content of the visualization to a familiar visual pattern. His mother and brother acknowledge this, and Esmeralda changes her representation on paper to better reflect what the family interpreted from the visualization.

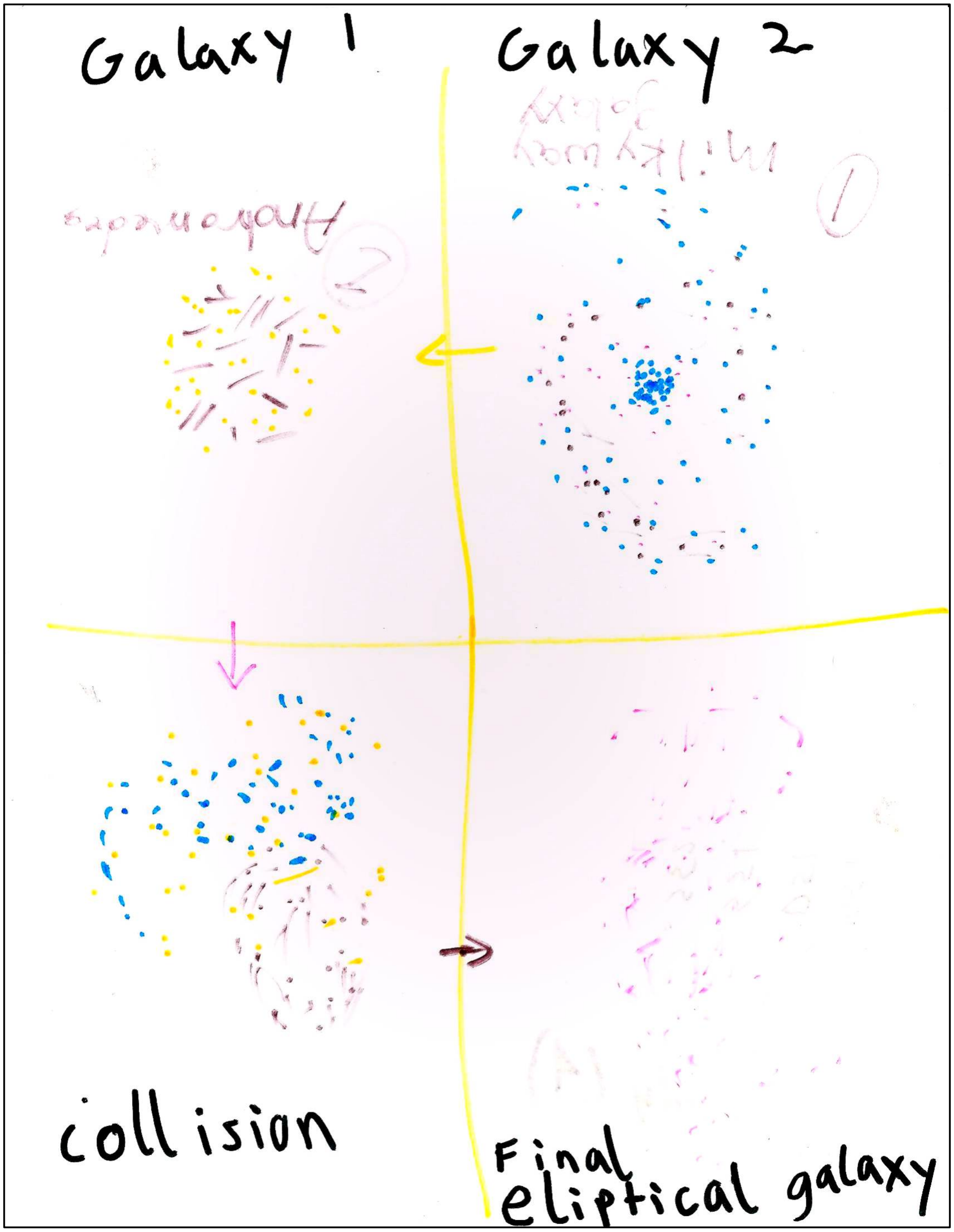
In this next scene from the same family, Joseph brings up the dynamics by giving information about the galaxies "facing around" each other, Sara discusses how to illustrate this dynamic on the paper, and Joseph suggests using a plus sign to indicate the dynamic. Finally, we again see the mother taking on the role of coordinator, splitting the paper into quadrants to allow multiple drawings, despite the fact that her children had indicated that they wanted to illustrate the transition between stages more fluidly.

Utterance	Action	Coding
JOSEPH: Well it had two kind of facing around <???>....,[uses hands to indicate the movement of galaxies around one another]	Give, Info	G2
SARA: So I think you have to draw the other one [motions her finger in a circle next to the blue-brown-red galaxy they have drawn] the other one coming	Solicit, Action	G1

down...		
ESMERALDA: And that was like...what color do you think the other one was like [reaches into case, gets yellow marker]	Solicit, Info	
JOSEPH: We should do a plus sign [motions between the galaxy and the spot where his sister has indicated]...these two plus [indicates a plus sign between the galaxy and the space indicated by his sister], and then [motions toward other side of the paper] and then draw what happened after	Solicit, Action	G2, S1
ESMERALDA: [Uses yellow marker to cut the drawing space in half, with galaxy on one side of the line] Well... [starts to draw another line to cut the picture into quarters, decides against it, splits the half closest to her, so that the galaxy they have drawn is in a box taking up about a quarter of the page]we'll just go like that	Give, Action	

The Gonzalez's final drawing is shown in Figure 15.

Figure 15. The Gonzalez' family's drawing.



Example 3: Juan and Michelle Identify the Dynamics without the Components

Juan, Michelle and Elenda saw a visualization that depicted the formation of structure in the Universe, described in Appendix B, Visualization 2. Juan and Michelle never agreed on what to call the structure that they drew, but they could see that things were travelling through it. They spend the majority of this scaffolding scene identifying a bright ball in the center of the visualization, which is reflected in the high rate of C (identifying components) coding. They agree that there are galaxies in the visualization, but refer both to the large structure at the center, and the smaller structures making it up as "galaxies." They also use the scientific word "filaments," which we had used in class to describe this kind of structure. Throughout the following scaffolding scene, they negotiate what to call the bright center of the filamentary structure, which is identified in the narration as supercluster of galaxies. What they decide is that there are filaments emanating from the center, that it was bright, and that it was moving in relation to the galaxies, all of which is accurate.

Utterance	Action	Coding
JUAN: Okay. We saw that one star. Whatever it was; galaxy. [Draws a large yellow circle in the center of the page]	Give, Info Give, Action	C2
MICHELLE: Do you want to draw the sun?	Solicit, Action	C2
JUAN: It wasn't the sun, it was like yes, it was like that galaxy, like.	Give, Info	C2
MICHELLE: Like this. [Articulates lines on the page	Solicit, Action	C1

with the pen]		
ELENA: [Draws purple lines emanating from the center]	Give, Action	
JUAN: Yeah, like filaments and stuff.	Give, Info	C2
ELENA: Así. *{like this}* [drawing lines]	Give, Action	
JUAN: You can draw more filaments. You saw it, obviously.	Solicit, Action	
[All begin to add filamentary structure with various markers]	Give, Action	
MICHELLE: No, I can't do it. [inaudible 0:02:59] En este {*in this*} like, draw little tiny, tiny things that make it seem like they are little galaxies.	Solicit, Action	C3
JUAN: There were galaxies in that thing?	Give, Info	
MICHELLE: Yeah but <u>they looked super, like, like dust</u>…please tell me these little things are galaxies.	Give, Info	C3
JUAN: What else?	Solicit, Info	
MICHELLE: What is this? [Points at yellow spot in the center]	Solicit, Info	C1
JUAN: It's like that one thing you probably have seen the whole time, you know it's like whatever star it was. Or I think it was a star or a galaxy. I don't know.	Give, Info	C2
MICHELLE: Light.	Give, Info	C2
JUAN: Light, really?	Acknowledge, Info	
MICHELLE: Yes, it was some kind of light. It was	Give, Info	

some kind of light.		
JUAN: It was going through. Traveling obviously, you can tell.	Give, Info	G2
MICHELLE: The center of the Universe [touches the yellow circle with her finger]	Give, Info	C2
JUAN: No [Michelle giggles]	Acknowledge, Info	

Michelle identifies that the structure of the filaments as made of galaxies, which is accurate. Notice Michelle's use of the attributional analogy of the galaxies as "dust" in order to indicate how numerous and small they appeared (underlined in the data). Later, when I asked them what the yellow spot was in the interview, Juan described the relationships in the system without using specific vocabulary. He used the attributional analogy of the spider web to describe the shape of the visualization:

JUAN: "That was like the bright light that was going through the whole thing pretty much and this is the light that passed over it. These are the filaments that we saw. Obviously they're all connected like spider webs."

This attributional analogy describes well the interconnected nature of filaments in the large scale structure of the Universe, at least on an aesthetic level.

Juan, Michelle and Elena's final drawing is shown in Figure 16.

Figure 16. Juan, Michelle and Elena's drawing

Example 4: Maria and Yesmin use Relational Analogies

Maria and Yesmin saw a visualization depicting the collision of two galaxies (more information in Appendix B, Visualization 1). They made sense of this merger as part of a larger cycle of galaxy formation in which galaxies collide to form new galaxies, which then collide with other galaxies to form new galaxies, etc. (see Figure 17). In the following scaffolding scene, Maria and Yesmin build on one another's observations of the motion that they saw in the visualization to construct a more robust understanding of what is going on. The scene culminates in Yesmin theorizing about the dynamics by comparing it to the dynamics of objects in a magnetic field. Although gravity is not magnetism, there are a lot of similarities, and this is definitely a fruitful relational analogy because it allows Yesmin to map the unfamiliar behavior she sees to something more familiar, which she can return to later.

Utterance	Action	Coding
MARIA: It's going into it, right?	Give, Info	G2
YESMIN: Yeah, but I don't know if you noticed sometimes instead of going into it, it would just pass by [makes a motion with her hand]	Give, Info	G2
MARIA: Yeah it wouldn't get like attached to it	Give, Info	G2
YESMIN: Think about it like in a magnet and like, like that thing, that circle that was going in circles wasn't similar to a magnet but similar to some of that, that like didn't have enough strength to pull the other ones into it.	Give, Info	G2

Yesmin's analogy may not be perfect, but analogy in science is rarely perfect (Taber, 2001; Sterman, 2002). The dynamic that she borrows from the magnet is that of an attractive force that is dependent on the variables of the system, and thus doesn't always have "enough strength." Here she identifies a hidden component of the system, one identified by several other groups: gravity.

Several minutes later, when the women are drawing, they discuss these dynamics again. Maria is more tentative, while Yesmin is more confident about her understanding, which becomes clear when Maria frames her action moves as questions to get Yesmin's approval before translating the idea into drawing.

Utterance	Action	Coding
MARIA: Should I just draw dots like, that this go into that?	Solicit, Action	
YESMIN: Yeah	Acknowledge, Action	
MARIA: [draws smaller circles and indicates with arrows that they are moving toward the larger circle, passes the marker to Yesmin]	Give, Action	G2
YESMIN: But some of them, like these, are just going to pass by [draws some particles with arrows indicating that they pass by the larger circle, then pauses]	Give, Info	G2
MARIA: Put like right here just passing by [points beneath the larger circle]	Solicit, Action	

YESMIN: Yeah, like this one is going to go down [gestures with her finger a trajectory toward the large circle], and this one is going to pass by [gestures with her finger a curved trajectory around the large circle]. Then this one is going to go in, and this one is going to go in. And then after that we're going to draw an arrow, like right here.	Give, Info Solicit, Action	G2

In Yesmin's last utterance, she notices non-linearity in the system. She points out that despite the fact that all of the material begins by going "into" the galaxy, its not that simple, and some material will pass through, or pass by. The cause-effect relationship between moving toward a galaxy and being absorbed into the galaxy is not linear. Yet a later interview revealed that she attributed the patterns she saw to the strength of individual galaxies, rather than thinking about the large scale effects of interactions between galaxies, so this was not emergent thinking. When I asked them about what they had chosen to depict, they drew on the magnet metaphor again. The metaphor gives Yesmin the vocabulary she needs in order to describe the complex dynamics of what she saw, without the scientific lexicon that is so new to her.

YESMIN: Okay, so on the video, I learned that--well, we both learned--that it was starting to form, like it was rotating, and as it was rotating as well, like it started to get like …
MARIA: Collecting the dust.
YESMIN: Collecting the dust and the gasses, and some of them were just …

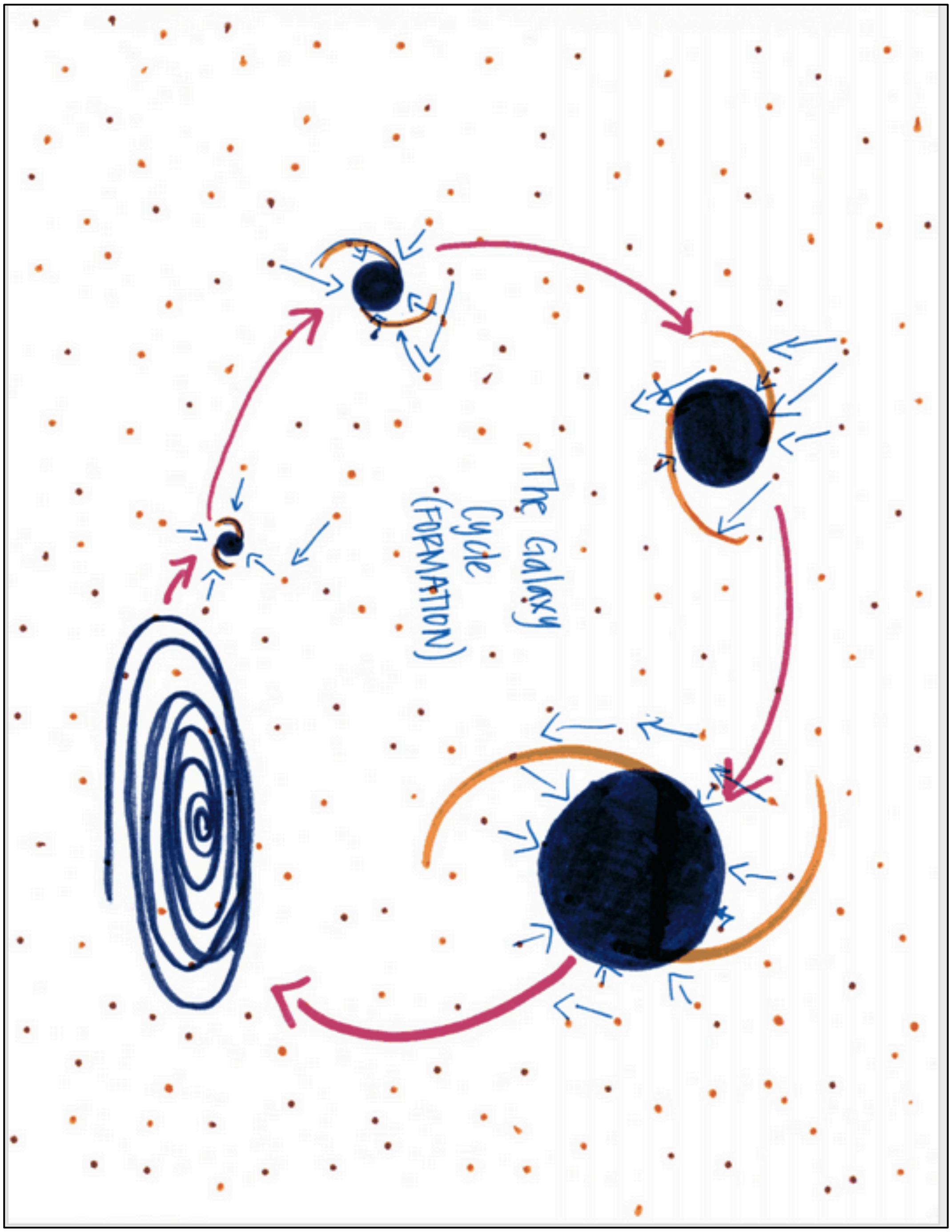
MARIA: Passing by.
YESMIN: Some of them would just pass by, and like, I thought kind of this as a magnet as it was rotating. Like, some of them were … like some of the galaxies would like have the strength to like to pull it in towards it and become one galaxy, and on this, like most of them would end up like passing by a lot, and then it would just stick, and it would just form like a natural galaxy, and it would just eat that, and it's like a world would start again.

In this last quotation from Yesmin, there are two relational analogies. One is that of the magnet, which she and Maria return to over and over to describe the dynamics of the system. The second is a new one, that of the galaxy "eating" passing material. This analogy describes the way that stars and dust ejected by the gravitational interaction between the two galaxies appear to be absorbed into the newly forming galaxy. Whereas the magnet analogy allows the students to express the force of gravity as an attraction between two objects, the eating analogy allows the students to express their observation of the differential effect of this attraction on objects of different masses, with the less massive object accelerating significantly more.

Yesmin and Maria were not the only group of participants who noticed and theorized about this kind of motion. Alisandra and Lily talked about it in relation to the motion of galaxies passing in and out of clusters at the intersection of filaments. A description of the visualization that they saw can be found in Appendix B, Visualization 3. Alisandra told me that she "didn't really listen to the narration as much because the visuals are much stronger, they make more of an impact…they make it feel more real." As an example of how much more she took from the visuals, she went on to describe how the galaxies “moved into clumps, and then passed through” before heading back again. The narration had not explained this, she said. Her partner, Lily, reiterated this motion, saying that what really stuck out to her was the motion of galaxies through the filaments instead of “getting stuck” and using her hands to illustrate with gestures.

Maria and Yesmin’s drawing is shown in Figure 17.

Figure 17. Maria and Yesmin's drawing



Discussion

Cosmological sense-making

In terms of CSM indicators, actions mediated by those concepts and practices associated with cosmological literacy, students were very focused on identifying components of the system, and their relationships to other components. This included not just the simple naming of things, but identifying what the structure of the Universe is made of, or what galaxies are made of, coded as G3, as in the following interaction:

Saul Perez	What are you drawing?
Maddie Perez	A big web.
Saul	A big web?
Lizvette Perez	The big web. She thinks the one that was up there was a big web.
Saul	What do you think the big web was made out of?
Maddie	Galaxies.

Student activity included extended discussion of dynamics due to gravity (galaxies fusing, stars pulling, objects coming together). 9 of 11 groups included G1 and G2 coding. However the word gravity came up in the data only twice (G3 coding). Only one group mentioned gravity explicitly: Eugenia, Esperanza and Ana. The group was discussing the galaxies, and how they came together. Esperanza added that this happened "por la gravedad" *{by gravity}*. Two minutes later, Esperanza repeated the phrase when the group was discussing the motion of the second galaxy back toward the first galaxy. Eugenia, Esperanza and Ana's drawing is pictured in Figure 18. Notice that gravitational "atración" is labeled.

Despite the lack of explicit mention, in the interview afterward, all students demonstrated an understanding of gravity as a force that brings things together, and as something involved in the visualization. In the students' discussions amongst themselves, instead of using the explicit concept of gravity, students used everyday talk like the galaxies are "coming together," or more familiar metaphors like that of the magnet.

It is hard to make generalizations about observability, because only four groups watched a visualization that mentioned dark matter (see description in Appendix B, Visualization 3). However, it is worth noting that these groups did not mention dark matter at all. And while several groups discussed the order of time-steps, coded as S1, only two groups mentioned the large time scales involved. This is interesting because it tells us what facets of cosmological literacy are mediating sense-making around the visualizations: primarily identifying the system components, and the dynamics of the system. The visualizations helped students organize the timescale of the dynamics, but only rarely did they help them to understand and apply the immensity of the timescale. In this case, they did not appear to help students think in terms of observability at all.

Figure 18. Eugenia, Esperanza and Anas' drawing

Hybrid Language

Students spent the majority of time identifying components of the system, and describing the relationships between these components, but rarely used the agreed upon scientific vocabulary to do so. Hybrid language and analogy allowed the students to observe and describe processes accurately, but without a shared vocabulary, the basic components of the system were lost. For example, words like "galaxy," "sun," "light," and "thing" were sometimes used interchangeably. What this indicates is that the visualizations have a lot of potential for getting students to think about these systems and the dynamics of these systems, but if we want them to begin articulating the components of the system scientifically we need additional supports, outside of the visualization. This is especially important for NDLB students, for whom learning to science talk is even less intuitive.

In the classroom, this can be facilitated by instruction designed to encourage hybrid language, while reinforcing new vocabulary words explicitly. Students use of hybrid language is typical (Ash, 2008), and should be encouraged rather than discouraged in the classroom (Lemke, 1990). Research has shown that science classrooms that emphasize hybrid discourse by making academic language transparent foster science achievement for all learners (Lee and Fradd, 1998; Brown, 2004). When students actively participate in talking science together with authentic content and contexts, using a combination of vocabulary and discourses, they will gradually adopt scientific ideas and language (Lemke, 1990; Ash, 2008). This requires educators to give students opportunities to practice science talk as much as possible in the classroom.

Visual Analogy

Participants relied on various visual analogies to make sense of the visualization. According to Gentner (1989), "analogy is a mapping of knowledge from one domain (the base) into another (the target) which conveys that a system of relations that holds among the base objects also holds among the target objects." Six out of the eleven participant groups used analogy in their activity, sometimes several different analogies. For example in the Perez family, Saul Perez told his kids that "it looks like the nervous system." Later, his daughter Maddie added that "it looks like a spider web." Both of these metaphors refer to the way that the visualization looked, allowing the students to visualize the large scale structure of the Universe. However, this analogy stops short of describing the dynamics of the system. We call such analogies "attributional analogies." Gentner (1989) calls attributional analogies "mere-appearance matches," which I believe downplays their importance in co-constructing more complex scientific analogies and explanations, particularly when working with complex dynamic visualizations. In interpreting a dynamic visualization of a new phenomenon, anchoring the visual information in the familiar serves to bring the science content closer to the students' experience.

While I see attributional analogies as productive tools, relational metaphors are more sophisticated. Relational metaphors are mappings of relational structure, such as Yesmin's magnet analogy. Nothing in the visualization looked like a magnet, but the components moved toward and away from one another in a way that Yesmin found to be analogous to the various magnets.

Some researchers criticize analogy as a tool for teaching science, pointing out that no analogy is perfect, and that this can introduce misconceptions. Mary Hesse, whose 1966 book on the importance of analogy to science is one of the seminal texts in the cognitive approach to the topic, presents the example of quantum mechanics (2001). The mathematics of quantum mechanics requires that elementary particles such as electrons be treated both as particles, and as waves. Thus to understand the atom, we cannot use the analogue of the solar system, which compares electrons to planets, nor can we use the analogue of a pebble in a pond, which compares the regions around an atom where there is a high probability of finding the electron to the ripples emanating from the point at which we dropped the pebble. There exists no good analogy that will help us understand wave-particle duality, and this has posed a major obstacle to both scientists and educators attempting to translate mathematics into conceptual understanding.

This traditional conceptualization of analogy is limited, however, by its adherence to a conceptual change framework. If we expand our vision of the learning trajectory to see students ideas as productive and situated, then the danger of analogy seems less imminent. The students are drawn to analogy to make the unfamiliar familiar, and in a domain like cosmology where phenomena are all very unfamiliar, I believe this can be a powerful tool. In addition, research has shown analogy to be productive for science learning: Hohenstein and Ash (in review) observed analogy in use among family groups at a small marine science center in California. They found that analogy was helpful for learning because it allowed learners to communicate relationships between concepts in different domains and to imagine complex causes or mechanisms within the material in a way that helped them understand.

Conclusion

These results imply at the least that dynamic visualizations bring something important to the table. When engaged in cooperative, object-oriented activity students are making sense of the components, movements and interactions of the system. Even if they don't yet have the content-area English vocabulary to describe what they see, they are noticing and theorizing about it using hybrid language, (everyday/scientific and Spanish/English) which has been shown to a be a powerful tool for learning science, especially in classrooms with students from non-dominant cultural and linguistic backgrounds (Ash, 2008; Warren et al., 2005). The low linguistic demands of the visualizations allow the students to engage directly with the content, using powerful tools like visual analogies, both attributional and relational, to discuss and refine their understanding of the system. By drawing the visualization together, the students are engaged in meaningful activity that encourages such discourse naturally. This lends support for incorporating collaborative activity like the drawing into classroom and informal learning settings to function as an improvable object.

In the classroom, visualizations can be used to build a more complex understanding of what is going on. It is one thing to describe gravity and how it affects the motion of galaxies, but seeing the visualization brings this motion to life, and gets students thinking about the motion they see, and what could explain it. Teachers can use visualizations to introduce the physicality and motion of a system, encouraging hybrid discourses and analogy, and eventually guiding the activity to include more and more scientific language and practice.

Michelle's insistence that it is "some kind of light" could be interpreted as simply wrong by a teacher or researcher. But by "listening past" her words (Moschkovich, 2002; 2008; 2013), we see that it is not really an attempt at categorization, but rather it is a description used to make sense of what she has seen by aligning it something familiar. These results lend support to the imperative that teachers be trained to listen past English fluency, and give NDLB students opportunities to demonstrate their competency using gestures, hybrid language and various alternative modes of communication. In addition, instruction could build off of her observation by investigating what the word "light" means in a scientific context, where light in space comes from, and why it might be used in the visualization.

Access to science education tools that are designed to be inclusive of diverse ways of knowing and doing science is a critical condition for the success of traditionally under-represented students. According to Lee, 1999, "science learning and achievement occurs when students successfully participate in Western science, while also engaged in alternative views and ways of knowing in their everyday worlds" (p 91). If educators and designers of educational materials ignore the learning patterns of this country's changing population, their classrooms and informal learning institutions are unlikely to flourish in the coming decades. More importantly, by not addressing the needs of this "new mainstream" (Rodriguez, 2004), they will be complicit in a biased system that serves to reproduce persistent social inequities…the "perpetuation of institutional values and relationships that safeguard dominant power structures" (Darder, 1991, p 4). In the next chapter, I investigate the role that visualizations play in activity at an informal astronomy learning institution, with an eye for the ways in which discourse and practices might better serve the needs of all visitors.

Chapter Three: Contradictions, Historicity and Learning at an Urban Planetarium

In this chapter I present a case study of an urban Planetarium trying to define its goals at a time of transition, during and after the development of a groundbreaking planetarium show featuring dynamic visualizations. I look in particular at the role of historicity and contradictions in the multi-voiced network of activity systems of the planetarium staff and consultants, and of visitors. My analysis reveals several historical contradictions that appear to impel an institutional shift toward affective goals (such as attitudes toward science, or enjoyment of the experience), and drive the implementation of immersive visualizations. In some ways, this shift aligns well with the object of visitor activity; many visitors are seeking to "experience space" and participate in the shared cultural activity of going to the planetarium. However, visitors' number one expressed goal was still to learn astronomy content. My results indicate that those people who are learning astronomy content in a way that aligns with the intent of designers are doing so by relying heavily on their own prior knowledge. In my conclusion, I problematize the implications of this result, pointing out that affect may not be a sensitive enough instrument to detect disparities in visitor experience, and that the discourse around affect tends to conceptualize certain visitors as deficient.

Introduction: Visualizations as tools to present the invisible

Science centers and museums are, in a way, the complete opposite of the science laboratory. Whereas the everyday activity of scientists works toward the object of constructing fact and stripping it of all social factors, de-contextualizing knowledge so that it becomes an objective tool for the use of constructing new facts (Latour and Woolgar, 1979, p 28), the work of an exhibit designer in a modern science center is to re-materialize science, re-contextualizing it and presenting it to museum visitors who are not necessarily inculcated into the language and tools of the trade (MacDonald, 2002). This presents a dilemma for staff in how to contextualize content (Allen, 2004) in a way that is accurate, facilitates understanding, and feels relevant to a diverse audience.

These questions are particularly important at planetariums, where the "growing invisibility of science" (MacDonald, 2002) is most keenly felt. As our understanding of the Universe has grown over the past few decades, astronomy content has moved further from things we can see with our eyes –stars and planets –to things that are only detectable indirectly by increasingly sophisticated instruments and telescopes, like dark matter, black holes, and extrasolar planets.[29] In the

---

[29] The ability to articulate the connection between the visible and the invisible is a fundamental facet of cosmological literacy, as is the ability to work with deep time and deep space.

planetarium, it is the job of astronomers, historians, artists, and educators to make all this invisibility visible. Whereas the aquarium and the natural history museum can contextualize science content by putting the remnants of real animals and plants on display, the planetarium is faced with the more daunting task of determining how to contextualize content that is billions of light years away, invisible, and on a scale that is literally incomprehensible to the human mind.

In chapter one, using the example of color, I showed how important it is that we think carefully about how visualizations are designed. In chapter two, I looked more closely at learning using visualizations. In this chapter, I take a step back, looking at the context in which these visualizations are embedded, and asking: what are the challenges of using this tool in context, and how are they being addressed? To understand this, we need to look closer at how visualizations are used, and toward what object they are oriented.

Research Design

It is almost impossible to talk about the implementation and potential of dynamic visualizations without situating them in a specific learning context. To study visualizations in the laboratory, bringing in participants for the sole purpose of viewing the visualizations, would obfuscate the vital importance of the activity in which the action of viewing and making sense of the visualization is embedded (Lave & Wenger, 2001; Engeström, 1987). This is why I chose to embed my investigation of visualizations in a context-rich case study. Yin (2003) defines a case study as "an empirical inquiry that investigates a contemporary phenomenon within its real life context, especially when the boundaries between phenomenon and context are not clearly evident (p 13)." The boundaries between the activity at the planetarium and the visualizations central to that activity are not well defined. Visualizations are central to the activity of both staff and visitors, serving as an object toward which all kinds of activity can be oriented (exhibit production, fund-raising, museum attendance, content learning) as well as mediational tools for these and other such activities. This complexity calls for a methodology that is deeply sensitive to context and historicity, such as case study, which preserves the details necessary to describe dynamic networks of activity.

My goal in the chapter is to look closely at the case of the Adler Planetarium in order to better understand the role of dynamic visualizations in this particular context. In other words, what lessons can be learned from this case (Lincoln & Guba, 1985) in regards to the use of visualizations to present astronomy content? I have divided my research questions into three parts as follows:

1) What are the shared objects of dynamic networks of activity around visualization production and use in a large, urban planetarium and how do they affect learning?
    a. How does the historical context of the planetarium create contradictions in the activity and discourse around visualizations, and how does this manifest itself in the object of activity?
    b. What is the object of visualization-mediated visitor activity at the planetarium, and how does this fit within the larger network of activity?

c. What knowledge resources are visitors drawing on in order to mediate activity around figuring out visualizations?

To answer these questions, I use cultural historical activity theory (Engeström, 1987) to reveal intersections and contradictions in the network of activity that make up the case. I will structure my analysis around these research questions, with a focus on the activity theory principles of contradiction, historicity and multi-voicedness to reveal sites where learning is taking place (Engeström, 2001; Engeström & Sannino, 2010).

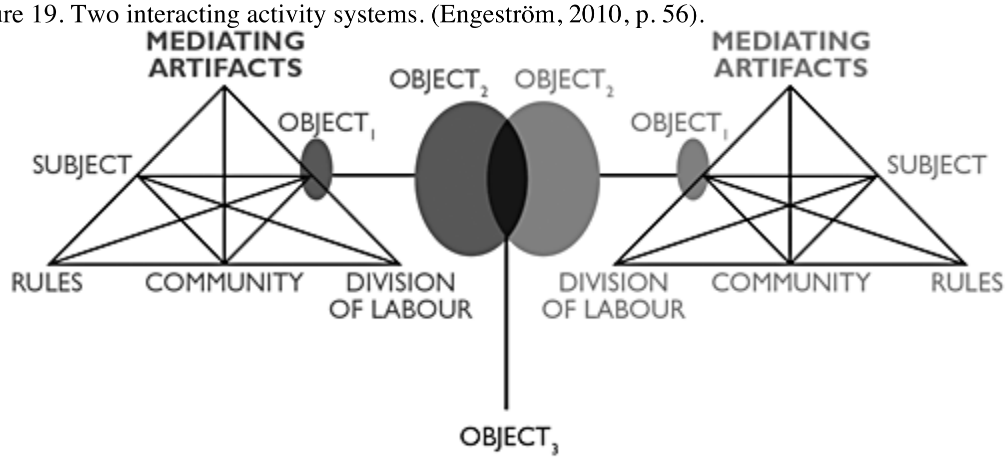
Methodology

A case study involves research into an issue that is explored through a single, in-depth, bounded case. A case study typically involves multiple sources of information (e.g. observations, interviews, documents), and results in a description of the case, and the presentation of case-based themes (Creswell et al., 2007). The analysis is not generalized, but rather embedded within the detailed context of the case, which means that case studies are often rich in detail. Case study research lends itself well to a pragmatic perspective that incorporates both qualitative and quantitative data (Yin, 2003). Within the case, I take on a cultural historical activity theory (CHAT) perspective to understand the learning that is taking place, and thus address my research questions.

My analysis relies on a third-generation CHAT perspective (Engeström, 2001), taking as my unit of analysis the dynamic network of activity systems bounded by the case, thus reframing social, historical and cultural context as an integral part of the phenomenon under study, rather than as a "container" for that phenomenon, or something tangential to it. My design could invite an apparent contradiction between case study methodology, which takes the case as the unit of analysis, and CHAT, which typically takes the activity system as unit of analysis. A traditional CHAT perspective would take on each activity system I identified at Adler as its own unit of analysis, however third generation CHAT introduces the dynamic network, in which the boundaries of activity systems can be fluid. I use the case of Adler during the development of a new planetarium show to bound and define my network, resulting in my case being the sole unit of analysis, thus resolving this contradiction.

The graphical model for understanding a simple (n=2) network of activity systems is shown in figure 12 below. While my focus is on how the activity systems dialogue with and challenge one another (Engeström, 2001), taken together my questions address the larger network of activity and the patterns that are revealed, and what it can tell us about the use of visualizations.

Figure 19. Two interacting activity systems. (Engeström, 2010, p. 56).



Such systems are inherently multi-voiced (Bakhtin, 1986) incorporating multiple perspectives and interests, and situated within communities with varied repertoires of practice (Gutierrez & Rogoff, 2003; Lave & Wenger, 1991). They are constructed within a historical context and shaped by the passage of time (Engeström & Sannino, 2010). Contradictions, defined by Engeström (2001) as "historically accumulating structural tensions within and between activity systems," are a vital location for understanding the dynamics of these systems and the networks in which they are embedded. It is through contradictions and the reactions they provoke over time, that activity systems are modified and changed significantly.

Historically accumulating contradictions provide the potential for the system to move through the collective ZPD, and begin enacting new forms of activity, what Engeström calls expansive learning. My first research question looks at historicity and contradictions in order to understand the potential for expansive learning at Adler on an institutional level, and reveal new objects of activity. Within such a model, the object motivating activity becomes a "moving target," a complex and shifting element constructed, deconstructed and reconstructed by activity systems and the interactions between them. My second research questions speaks to this object, looking at the object of visitor activity and how it overlaps with that of the planetarium staff. Central to the activity within each system are mediating artifacts, the physical, psychological, conceptual and semiotic resources used by subjects to shape their experience. My third research question looks at theses mediational means, asking how visitors to the planetarium rely on tools to shape their experience of the visualizations.

Methods

Data Collection

In order to study and model the network of activity systems at the Adler, I spent a month embedded in the planetarium in July of 2011, and another month in July of 2012, spending approximately 400 hours total on site. During this time I collected over 50 pages of ethnographic notes and reflective writing. I conducted 8 hour-long interviews with planetarium staff, leadership and advisors. Data also included several in-house documents regarding show objectives, script decisions, and meeting notes. Finally, my data included several historical documents (advertisements and an early museum guide) given to me by a participant who collected such artifacts.

In the first summer, I held 4 focus groups with groups of museum visitors, with between 5-10 visitors per focus group. Focus group protocols can be found in Appendix D. In the second summer, I collected visitor drawings, done following the planetarium show experience. I provided participants (in family groups) with a piece of paper and markers, with instructions to work collaboratively, and draw what they "learned" in the visualization. The word "learned" is vague, and was not elaborated on. It was chosen deliberately to provide a point of discussion among participants to encourage dialogue around the content of the visualization. 64 families drew pictures and explained them to me on the floor of the museum (data include drawings, written explanations and my notes), while 15 families joined me for a taped, extended interview in a semi-private room (data include drawings, written explanations, my notes, and video/audio transcriptions). Protocols for post-drawing interviews can be found in Appendix D. Both summers I collected online and on-the-floor surveys regarding visitor motivation and reactions to the show (n = 143).

The Case

The Adler has focused heavily on visualizations, with the construction of the brand new Grainger Sky Theater with some of the most advanced projection technology in the world, and the hybrid exhibit/visualization production studio called the Space Visualization Lab (SVL). The first show for the new theater was produced in-house. At the insistence of the planetarium president and the show's producer, both research astrophysicists, the show was designed around 4 real data visualizations: large scale dark matter evolution (see Appendix B, Visualization 3), a galaxy merger, a type 1a supernova, and a star passing by a super-massive black hole and getting ripped apart. This break from the traditional, didactic planetarium presentation is embodied in the choice to construct the show around a science fiction story about an extraterrestrial searching for his home. This choice was pushed back on by the Adler's astronomy department and other scientists involved in the production of the show, some of whom felt that such a story had the potential to be "hokum" and "disrespectful to the science." Museum members also expressed a nostalgia for more "traditional" planetarium shows. As a result, the second show produced for the new theater is in a format that more closely resembles the traditional planetarium show, with live narration, no fictional narrative, and a focus on what can be seen in the sky tonight. In addition to showing constellations, this show also relies heavily on large-scale data visualizations, including the Earth surrounded by satellites, and the distribution of galaxies in superclusters. In this study, I interviewed audience members from both shows, preserving data about which show each group had seen in order to take this into account during analysis.

Participants

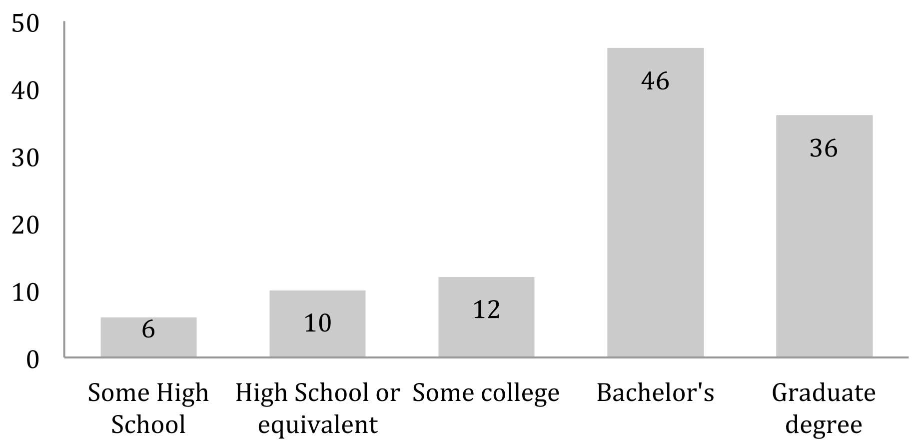
The participants in this case study included planetarium staff and consultants, and planetarium visitors. At the locus of these activity systems are the visualizations, which serve as a mediational tool for visitor learning created by staff, an object for visitor activity around making sense of content, and as an improvable object – a potential site of expansive learning for planetarium staff.

Planetarium staff: Planetarium staff and consultants were mainly located on site in Chicago, but included some partners at the University of California. These participants were typically either associated with the astronomy department at Adler, and had a background in science, or with the day-to-day production of the planetarium show, and had a background in either science or design. My participants also included Carl Sagan's son Nick Sagan who wrote the planetarium show, an executive staff member in the education department at Adler, and several administrative staff, including the former president of the Adler, Paul H.

Knappenberger Jr.[30] I interviewed a total of 8 planetarium staff/consultants.

Planetarium Visitors: The Adler receives significantly fewer visitors than the nearby aquarium and natural history museum, but is still a popular Chicago attraction. Especially compared to the aquarium, the planetarium serves a highly educated demographic, a fact that was explained to me by several staff during interviews, and was confirmed by surveys, shown below in Figure 20 (n = 110). 42% of visitors surveyed had a bachelor's degree, and 33% held an advanced degree. Only one third of those people with bachelor's degrees or above reported their degree being in a STEM field. I interviewed a total of 64 families on the floor with surveys and informal questions, and 15 families formally in recorded sessions in the SVL.

Figure 20. Educational background of planetarium visitors from surveys. This distribution is highly educated compared to the general population.



[30] Sagan and Knappenberger agreed that their anonymity was impossible, so their real names are used.

Coding and analysis:

I coded field notes, documents and planetarium staff interviews thematically using Atlas.ti[31], grouping quotations that treated the same theme together. I then chose to focus on those themes that addressed my research questions. Within themes, I grouped quotations together that took similar positions in order to construct a positional map of each theme and highlight multiple voices embedded in the activity. One of these positional maps can be found in Figure 21. These maps were used to address my first research question.

Coding for visitor data was also done in Atlas.ti. I first coded visitor responses using an emergent, iterative coding system for specific references to content and dynamics of the visualization. As the research developed, it became more interesting what resources visitors were drawing on to describe and explain the visualizations than what specific content they were referring to, so these codes were collapsed into broader categories to address my third research question. I also coded for general accuracy in explaining/drawing the visualization, based on the scientific explanation offered by the scientists and producers involved. The rubric for this was

---

[31] Atlas.ti is a popular qualitative data analysis software package with tools for locating, coding, and annotating findings in primary data material, weighing and evaluating their importance, and visualizing the complex relations between them.

simple: visitor interviews were given a score from 1-3. A score of 1 indicated that the drawing and interview were not related to science content from the visualization (i.e. the visualization showed a galaxy merger and the family drew the Earth). A score of 2 indicated that the drawing and interview were related to content from the visualization, but contained inaccuracies (i.e. the visualization showed dark matter evolution in the early universe and the family drew a filamentary structure and described it as stars). A score of 3 indicated that the scientific content of the drawing and interview were well aligned with the intent of the visualization.

Results and Discussion

Research Question 1: Historicity and contradictions

The Adler is in a place of transition, struggling to unite its historical mission with its responsibility to the community, all in the context of political pressure toward accountability. The Adler is an example of an institution making an effort toward expansive learning, or "learning in which the learners are involved in constructing and implementing a radically new, wider and more complex object and concept for their activity" (Engeström & Sannino, 2010). Such systems can only be understood "against their own history " (Engeström, 2001), so I will begin by setting out the historical context of the Adler Planetarium and Astronomy Museum, and then describe two tensions that have emerged from my examination of the Adler's historicity.

The Adler Planetarium and Astronomy Museum was born of a very particular time and place in the history of the United States. Unlike the grand historical institutions of Europe, the idea of the museum primarily as a place for "the student," "the technical visitor," or "the specialist" (MacDonald, 2002) was never a part of the Adler's "mythology" (Latour & Woolgar, 1979). Instead, the intention behind Adler's collections and exhibits was always aligned with the more modern, liberal vision of the museum, as a means through which the local masses might "civilize themselves" (Bennett, 2013). In his presentation address when the museum opened in 1930, primary benefactor Maxwell Adler explained: "Chicago has been striving to create…facilities for its citizens of today to live a life richer and more full of meaning than was available for the citizens of yesterday" (Fox, 1932, p 5). This vision was taken on by Philip Fox, first director of the Adler (1930 to 1937), who wrote that "if all persons could be informed of the successive advances of science, if the phenomena and the laws which govern them and which may be derived from orderly consideration of them could be presented in such a ways as to win general understanding, the progress of learning would be greatly accelerated" (Fox, 1932, p 5).

Fox, whose legacy still shapes the culture and physicality of the Adler, was a fanatic for detail, recounting every detail of the new planetarium's construction in a guidebook to the institution, from the exhibit halls to the air conditioning manufacturer, even noting and explaining why the zodiac signs around the outside were accidentally put in backward (Fox, 1932). The stars in the background of the illustration on the cover of the guidebook are in accurate configurations, a detail that might be lost on the typical reader. This sense of responsibility to "the facts" parallels the responsibility described in accounts of traditional museum culture to protecting "priceless artifacts" (MacDonald, 2002), and emerged clearly from the data in this study. If we take Adler's primary responsibility to be "to prepare in form for easy comprehension exhibits to illustrate the phenomena and laws of those sciences which walk hand in hand with mathematics," (Fox, 1932, p 5), then its most important artifacts are not its ancient astrolabes and historical telescopes, but the science itself: the facts as constructed by scientists (Latour and Woolgar, 1979). Both Adler's astronomers and the scientists who work with the Adler on a regular basis take their responsibility to preserve scientific fact very seriously, and will occasionally take up arms to prevent "pure data" from being "diluted" by educators and artists. This sense of responsibility for curating scientific fact is part of the first tension that emerged from my data: that of the historical role of the Adler as curator of scientific fact, and the emerging role of the Adler as an experiential, educational institution.

Contradiction 1: Responsibility to science in a visitor-centered institution

Paul Knappenberger, president of the Adler during the time this research was taking place, joined the planetarium in the early 1990s. Knappenberger pushed to strengthen ties with research astrophysics by maintaining a good sized staff of working astronomers, most of whom have joint positions at the Adler and local Universities. Concurrent with this push to strengthen ties with the astronomical community, the museum embarked on several large scale projects designed to "transform the Adler from a traditional planetarium into a 21st century space science center," pushing the Adler further from being a place of collection, toward the interactivity of a "science center" like the Exploratorium in San Francisco. Still, the Adler is particularly proud of its history, and retains a sizable history department. It also maintains several historical exhibitions including a collection of astrolabes, despite its declining popularity in comparison to the more flashy, science-themed exhibits.

The tension between collection and experience is not new, nor is it unique to the Adler. In her ethnography *Behind the Scenes at the Science Museum*, MacDonald (2002) documented the development, execution and reception of a new exhibit at the Science Museum in South Kensington that was directly inspired by the Exploratorium. Much like the Adler, which differentiates itself from other planetariums by serving as both a planetarium and "Astronomy Museum," The Science Museum differentiated itself from other "science centres" by emphasizing that they had objects (artifacts), and were therefore more than just a centre...they were a museum. The exhibit in MacDonald's study is being developed by six women in the context of shift in museum culture worldwide, away from this focus on objects and connoisseurship toward an emphasis on visitor experience. This tension between preservation of fact and artifact, and improving visitor experience and education, manifested itself through a tension between specialist curators, who felt a responsibility to display objects in respectful ways to people who will appreciate them, and a new generation of curators with a very different vision of how an exhibit should look. Unlike many exhibits in the past, the women involved in designing the exhibit wanted their creation to be "busy," "hands-on," and "fun" (MacDonald, 2002)

At the Adler, this movement toward "busy," "hands-on" and "fun" included a big renovation, a new exhibit that allows young children to simulate space travel and exploring Mars, and the expansion of the education department. Across the departments of education and astronomy there is much talk of "backward exhibit design," "focus groups" and "learning goals," concepts that position visitors as consumers who should be prioritized over fact and artifact.

The two pronged focus on research astrophysics and visitor experience has kept Adler among the top planetariums in the world, but it has also sharpened the traditional tension between their original mission as protectors of fact and artifact, and the emerging movement to serve the public as customers, consumers, etc. This tension is deeply rooted in the shift toward interactivity and experience widely associated with the Exploratorium in San Francisco (Ogawa, Loomis & Crane, 2009) and is summarized here by Weil (1999):

> When collections were at the core of the museum's concern, the role played by those in charge of the collection—keepers in your country, curators in mine—was dominant. In American museums, curators were literally the resident princes. With the evolution of the outwardly focused, public-service museum, curators have been forced to share some part of their authority with a range of other specialists: first with museum educators, and more recently

> with exhibition planners, with public programmers, and even with marketing and media specialists (p 13).

In other words, the object of the curators has always been the protection of artifact, while the object of educators and other has been to share such artifacts – a contradiction created by the historically new role of the museum. As one Adler astronomer put it, summarizing the words of a colleague: "the educators think the curators just want to teach all their obscure scientific points, and the curators think the educators just want to dumb everything down, [in a whisper] and they really do want to dumb everything down."

Note that this astronomer refers to himself and his fellow scientists within the curator role. At Adler there are traditional "curators," in charge of the extensive collection of historical astronomical equipment such as astrolabes. But there is clearly a sense that science is the central artifact, the thing being collected and curated. For example, one of the positions that emerged several times across interviews was that of the Adler's responsibility to protecting scientific accuracy, a position that echoes the traditional curatorial responsibility to protecting precious artifacts. Said one person involved in the production of the show, "if it is possible…to make it scientifically accurate, then you are responsible and it's disrespectful not to… I think we had to advocate because [the simulation] is totally scientifically accurate and it would be a shame to dilute that." Others felt more strongly that the visualizations should be impressive and beautiful. One planetarium staff member used dolphins to explain the planetarium's goal for the planetarium show: “Institutionally it's going to be our WOW experience…this is our big thing, these are our dolphins…if we were the aquarium. We don't have characteristic mega-fauna.”

These various positions are not embedded within individuals, but rather the participants moved fluidly between these positions. For example, whereas in one moment “inspiration” could be used to imply that everyone in the audience leaves with a sense of wonder, in the next it could mean weeding out those who aren’t built for science, and inspiring further those who are built for it to investigate further, all in the course of a single interview, a swing between responsibility to everyone, and responsibility to science and a couple of individuals. One person involved in production explicitly claimed to “see both sides,” using an example of a galaxy merger visualization that she felt was not scientifically accurate: “Choosing the galaxy that you're going to show merging, maybe if you show the red galaxies it just won't [be] too exciting at all, you won't inspire the audience and your show isn't effective. So, that's a really big challenge and I am not quite sure the best way to go about finding the middle ground with that, but on our side we did our best to make the aesthetics what they wanted them to be…but still sticking to our grounds in terms of the accuracy.”

A positional map illustrating the various positions that emerged from this contradiction is shown in Figure 21 below. On the x-axis is the responsibility expressed by museum staff and associates. Near the origin of the x-axis is the traditional role of the museum as curatorial, with an emphasis on preservation and contextual accuracy. Since at the Adler, this role is taken mostly by scientists seeking to not "dumb things down," I have labeled it "scientific accuracy." Further to the right is responsibility expressed to the audience, and the community as a whole. In order to understand the y-axis of this map, I will now introduce the second major contradiction that emerged from the data.

Contradiction 2: Accountability and the museum experience

Despite the responsibility felt by many at the Adler to protect the accuracy of scientific fact, almost everybody involved in the production of the planetarium show felt that the end goal of including visualizations was to "inspire" people and get them "excited about science." One staff member from the astronomy department explained that "the learning more wasn't so much the thing it was more I want it to be fun… for instance there aren't any learning objectives in the show. It's not like I have to learn the galactic center has a black hole." A producer told me that the choice to not include too much scientific information was deliberate, because when visitors see the visualizations "you're encountering these really exciting things and you're not given a lot of background on them, and any curious person would want to know more." Some participants also mentioned content learning goals, for example one astronomer posited that: "you want everybody to feel positive and affirmed and get some content and get a good attitude and maybe even want to learn a little bit more when they go home." But there was surprisingly little discourse around sending people home with new content knowledge, especially in regards to the visualizations in the new show.

This goal of “inspiring” rather than teaching content is often referred to as an affective goal. The phrase “affective goal” was on everyone’s tongue at the planetarium, and had recently been a topic of discussion at several staff meetings. Most people seemed to agree that the emphasis on affective goals was coming from the education department.

The reason for the shift to affective goals was addressed explicitly by two astronomers, an animator, and a member of the department of education. They cited the impossibility of addressing specific learning objectives due to the logistics of museum experience, and a corresponding expansion of the object toward immersive, knowledge-independent experiences like visualizations. Affective learning is defined as the manner in which we deal with things emotionally, such as feelings, values, appreciation, enthusiasms, motivations, and attitudes (Krathwohl, Bloom & Masia, 1973). A leader in the education department at Adler described her own shift to affective learning this way: “I have actually changed my philosophy a bit on museum education since I have been here -much more I think now on the affective and personal side of the learning equation, rather than on the conceptual side of the learning equation. You know the average of the stay time at any given floor interaction is about 48 seconds, which you are not going to get meaningful conceptual change – but you can reinforce…you can do some affirmation, you can provide a family kind of feel good message about science.” Another participant, an astronomer, echoed this sentiment, adding that by addressing affective goals, the museum can reach more people: “I think the reason why I love the informal science education environment in planetaria and museums, is that…we excite people about stuff…and then that opens them up to where they might go back and do it themselves." In other words, the planetarium will be better able to meet their goals across a broader portion of the audience if there is less focus on science content, and more focus on getting people excited.

This discourse has been gaining popularity in informal learning environments over the past several decades, and is based on the work of Bloom who categorized learning as being either Cognitive: mental skills (Knowledge), Affective: growth in feelings or emotional areas (Attitude or self) or Psychomotor: manual or physical skills (Skills) (Bloom et al., 1956). The pressure to identify various types of learning comes from neo-liberal political efforts to make institutions of education, both formal and informal, accountable to the tax-payers.

Emphasis on accountability has driven curriculum and instruction in U.S. classrooms over the past twenty years. Assessments designed to measure knowledge of specific sets of content standards, mandated by individual states, have dominated educational policy, and changed what goes on in the classroom. Too often these assessments are "contrived exercises that measure how much students have managed to stuff into their short term memory" (Kohn, 2000, p 7). Informal institutions have the advantage over schools that they are not constrained by standardized tests and the nationwide movement toward "accountability." However, the trend in museums in recent years has been toward a type of museum evaluation that constrains learning in similar ways, focusing on "behavioral objectives" (Darder,

1991) in the search for “certainty and technical control of knowledge and behavior.” This kind of evaluation is essentially standardized assessment of learning objectives, but with the burden of the implications placed less on the learners.

MacDonald (2002) recounts the following example from exhibit design: in an effort to attend to visitor experience, the museum higher-ups told the team that they needed to have explicit “messages” or content goals for visitors, not only because this would “frame” the exhibit, and keep it within certain bounds, but because it makes it easier to evaluate whether or not the exhibit is “working.” This emphasis on accountability meant a lot more wordy panels than originally dreamt by the team, and the explicit framing of the exhibit in terms of “target audience” became in part a way of defending an exhibition against criticism from others who were excluded from that frame. In this way, “effectiveness” might be increased and targets met, but only within a framework that had specified sufficiently tightly what effectiveness and targets were to be.

According to Hooper-Greenhill (2004), museums around the world currently “operate within an outcomes-driven political climate,” that requires them to continually “demonstrate accountability and social value” (p 151). According to Weil (1999), the modern museum is judged on two factors: “first, that the museum has the competence to achieve the outcomes to which it aspires —outcomes that will positively affect the quality of individual and communal lives—and, second, that the museum employs its competence in such a way as to assure that such outcomes, in fact, are demonstrably being achieved on some consistent basis” (p 7). In other words, just as the American school system has felt the pressure to increase assessment in order to prove its worth, so has the American museum.

Much of the emphasis on assessment in science museums has been focused on establishing learning objectives for new exhibits, and then evaluating those exhibits by surveying visitors, or holding focus groups. At the Adler, this process was a source of tension between educators and scientists. Scientists involved in exhibit design wanted to include more advanced topics in their exhibits, while educators pushed to include simpler topics that were more broadly accessible, and thus easier to measure. Affective learning goals, however, provided a comfortable middle ground, which may explain why everyone at the Adler was talking about them. Researchers and politicians alike agree that museums are places where people can be “inspired” (Hooper-Greenhill, 2004, p 166). By formulating objectives related to “excitement” and “interest in science,” the Adler could create a set of quantifiable goals, measurable through Likert scales and simple surveys, which could potentially be met regardless of science content. One member of the education department, whose job it was to stand at the exit and hand out surveys to visitors about their experience, told me that over time she had whittled her survey down to one question: “how would you rate your experience at the museum today?”

The emergence of a new shared object

Figure 21 below illustrates the strength of the discourse about affective goals at the Adler during the production of the new planetarium show. On the x-axis we see the historically emerging contradiction between the purpose of the museum as both curatorial and educational, discussed above. On the y-axis are the various positions expressed by staff of what kind of learning goals should be met, from cognitive to affective. The various positions that emerge at the intersections of these contradictions are summarized in the bubbles. The larger the bubble, the more often the position came up in the data.

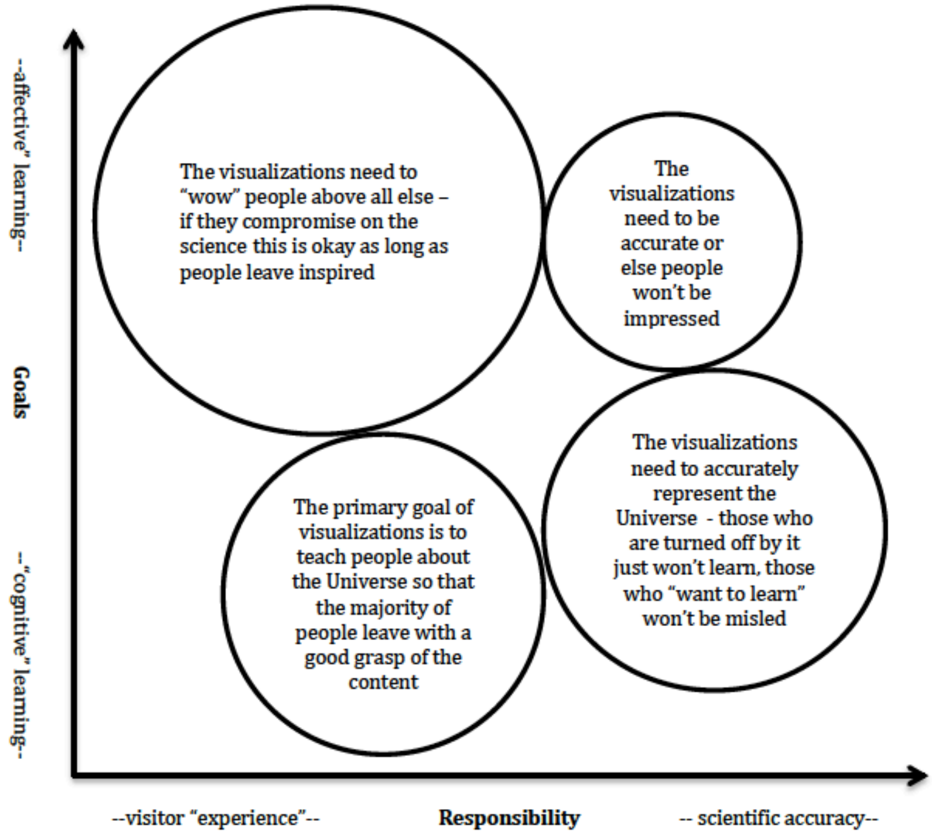
The position that linked accuracy with affect was rare, but did come up three times. The association was made between presenting real astronomical data in order to impress people. The astronomers stressed that “this is real astronomical data, not just animation,” and another member of the Adler staff explained that: “we show them things in a realistic enough way that they are interested to kind of continue finding out more about it.”

Another position that came up in the data less often was that accuracy was more important than accessibility, because if people were not open to learning, they wouldn’t learn anyway. This was expressed primarily by scientists involved in the production of the visualization, as in the following quote: “I think people learn the best when they want to, you can't make anyone learn something, and you can give the clearest explanation of stuff and…if they're not in the mood to absorb any of the material they're just not going to…” This quote and other like it echo a dominant deficit discourse in education around kids who “just don’t want to learn,” often applied to children from diverse cultural and linguistic backgrounds (Kohli, 2009; Gorski, 2008). This perspective can shift blame for unmet expectations away from institutions failing to meet the needs of diverse populations (Kozol, 1988; Oakes, 2005), and onto diverse learners.

The third position came up throughout the interviews across departments, and seemed to be held at least in part by all participants, but was usually mentioned only vaguely in passing, as opposed to affective goals which were mentioned more often That was that the visualization should teach people something about space.

Note that the most often expressed position was that of fulfilling responsibility to visitor experience by meeting affective learning goals. Remember that these positions were not embedded in individuals, for example a single individual might express the importance of accuracy, but also mention that small details can be compromised in order to make sure people were "wowed." Some participants used this position to justify the inclusion of fictional elements in the story, including the writer, Nick Sagan: "I mean scientists become scientists, many of them because [of] the science fiction they are exposed to. It doesn't even have to be scientifically accurate. My dad was a huge fan as a young boy growing up in New York of the Edgar Rice Burroughs' John Carter of Mars books, which are all rescuing princesses from firm green marshal warriors and my dad will read those books and see that John Carter was able to transport himself to Mars just by wishing it. … I came to the realization that if he was going to get to Mars and he needed something more… science."

Figure 21. Positional map of perspectives on visualizations in the new show



The changing discussion amongst planetarium staff, particularly at the intersections of various departments, reflects a new pattern of activity that would not have been possible in isolation, without the contradictions that have forced these discussions. For Engeström, these historically new patterns of activity constitute a movement through the collective ZPD, or expansive learning. The museum found itself at a the intersection of historically emerging tensions that led to the emergence of the position summarized in the largest bubble above, that while accuracy was certainly an important factor, "affective goals" should be the object of activity around visualizations going forward. Adler as an institution has been moving through an expansive learning cycle (Engeström & Sannino, 2010), constructing and renegotiating the object of visitor affect as a replacement for the historical objects of protection of artifact, or an enlightened citizenry. In the next section, I will look at where this object overlaps and interacts with the object of Adler's visitors.

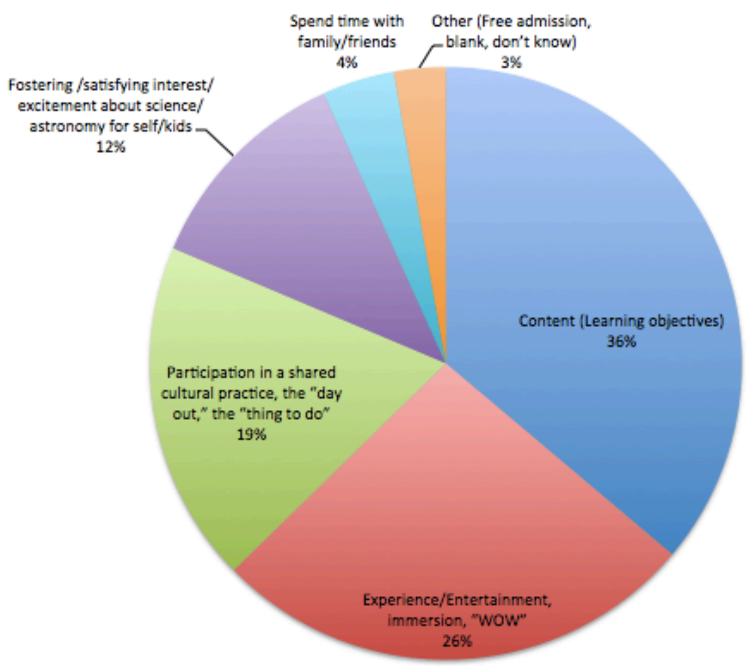
Research Question 2: Multi-voicedness and motivation

Visitors to the Adler, although they are relatively homogeneous compared to the greater Chicago community, represent a multi-voiced activity system with many dynamic motivations for being at the planetarium. Many seemed a little taken aback when asked what they hoped to get from the planetarium show. Some even told me they didn't know why they were seeing it. Several themes emerged from my conversations with visitors and informal entrance polls, which led to the construction of online and on-the-floor surveys asking visitors what they hoped to get from the planetarium show. These are summarized in table 7 below. Most visitors focused not on specific outcomes, but rather on their own motivation for being at the planetarium, and for buying tickets to one of the new shows. I will go through the three most popular motivations in more detail, and provide several examples from the data.

Table 4. Summary of visitor motivations for seeing planetarium show. (n=177) [32]

Content (Learning objectives)	64
Experience/Entertainment, immersion, "WOW"	47
Participation in a shared cultural practice, the "day out," the "thing to do"	33
Fostering /satisfying interest/excitement about science/astronomy for self/kids	21
Spend time with family/friends	7
Other (Free admission, blank, don't know)	5

Figure 22. Summary of visitor motivation for seeing planetarium show.



[32] This data represents 159 survey responses, but some responses fit into more than one category, so there are 177 data points listed.

Motivation 1: Participation in a shared cultural practice.

The third most popular object cited by visitors was that of the "thing to do" – what MacDonald (2001) calls the "day out." 33 visitors gave this response. This was often cited by out-of-town guests who came to the museum because it was part of their "Chicagocard," but was also common among Chicago residents who just felt that the planetarium was a good place to go, with or without kids. Here are a few examples from the data:

"We had never been to the planetarium before. We have already taken the kids to the [aquarium] and the [natural history museum], but we had never been to the planetarium, so we felt it was time to go."
"We live out in the suburbs, and we don't make it into the city very often, so we decided it would be nice to make the trip [to the planetarium]"
"We were visiting Chicago, and this is one of the places to see."
"We're not from Chicago, so we're trying to see all the museums."
"I visited the [aquarium] last time I was in the city for business, so this time I'm going to the [planetarium]."

These quotations imply participation in the cultural/historical ritual of "going to the museum" as a motivation in and of itself for museum attendance. Human activity tends to be motivated by participation in culturally valued collaborative practices oriented toward an object. Bourdieu associated museum patronage as a form of capital, "appropriated by ruling elites as a key symbolic site for those performances of 'distinction' through which the cognoscenti differentiate themselves from the 'masses'" (Bourdieu, cited in Bennett, 2005). While Bourdieu was referring specifically to the art gallery, the phenomenon is echoed in the modern natural history or science museum through the purchase of long-term memberships, and attendance at special functions and fundraisers. Patrons of the museum are participating in a cultural/historical ritual that distinguishes them as part of the elite, a positive distinction that motivates their attendance. My sample was largely white and well-educated, so I cannot say anything about whether this motivation is correlated with visitor demographic.

Motivation 2: They want to be immersed and wowed, and "experience space."

The second most popular motivation for being at the planetarium was to "experience space." This was a combination of words that was used verbatim 10 times by planetarium guests. This category also included guests who cited wanting to be "entertained," "blown away" or "experience something new." Some examples form the data are listed below. Here are a few examples from surveys:

"I want to experience space."
"I want to feel what it's like to be in the stars, and visit other planets."
"We want the kids to experience something that they can't do at home."

Motivation 3: Learning something about space

The most popular motivation for being at the planetarium was related astronomical content. Some visitors that I interviewed on the floor or during focus groups held this motivation in opposition to experience-oriented activity. These visitors, all of whom were adults, cited nostalgia for traditional planetarium shows, which they remembered to be more content-oriented. Traditional shows typically have stars projected directly onto the dome, and "what's in the sky tonight" is explained live by a planetarium employee. Interestingly, of the six guests who mentioned this nostalgia, three of them held memberships to the museum. This is not a large enough sample to generalize, but hints at a possible connection between membership and attachment to didactic learning experiences. In general though, the people I surveyed and interviewed spoke about being at the planetarium "to learn" about something having to do with astronomy. Others cited wanting their kids to learn, or "education." Here are some examples from the data:

"To learn about space"
"To learn more about galaxies"
"To learn more about the stars"
"Education for our daughter"
"For educational purposes"
"To learn about the Universe"

Negotiating a shared object

In answering my first research question, I revealed that the Adler as an institution has been moving through an expansive learning cycle, negotiating an emerging shared object of visitor affect rather than the historical objects of protection of artifact, or an enlightened citizenry. In many ways visitor data revealed that they share this object, expressing a desire to be "blown away" by technology, "get the kids excited about science," and "be entertained." However the object of activity can be elusive, especially when the system is multi-voiced (Engeström & Sannino, 2011). Visitors were multi-voiced, voicing orientation toward both traditional objects related to learning facts, and experiential objects, in addition to the participation in a cultural ritual of going to the planetarium. But it was clear that while many visitors wanted to be immersed, and were very pleased with the show, a more visitors thought of the planetarium as a place of pedagogy, someplace where learning would take place related to space, galaxies, stars, etc. This result was uncorrelated to background or education.

This did not mean visitors were not pleased with the planetarium shows. On the contrary almost every person interviewed or surveyed enjoyed their experience inside the planetarium dome, describing both shows as “immersive” and “like actually being in space.” One audience member gushed about the original science fiction show that she “came back today and saw it twice, I loved it so much, especially the immersive experience.” But the majority of the gushing praise was for the immersivity as it related to expressing space content: “I didn’t know there was so much room in the Universe, it was amazing,” said one audience member. Another translated for her friend, saying that “she did not need to speak English, the feeling, it was so much deep feeling around you,” a quote that demonstrates the promise of this medium for learning environments with a high percentage of NDLB students when scaffolded correctly.

Knowing the potential of this medium to draw in all kinds of learners, it is important that we look at the places where visitor object overlaps with Adler’s object to make sure that the institutional shift toward affective goals is serving visitors. The ubiquity of positive reactions to the show suggests that the planetarium is meeting its affective goals with this show. The show is functioning as the “dolphins” of the Adler Planetarium, bringing the wonders of the Universe down to Earth in a way that was previously impossible. In the next section I look very generally at what visitors were taking away from the show in terms of cosmology content.

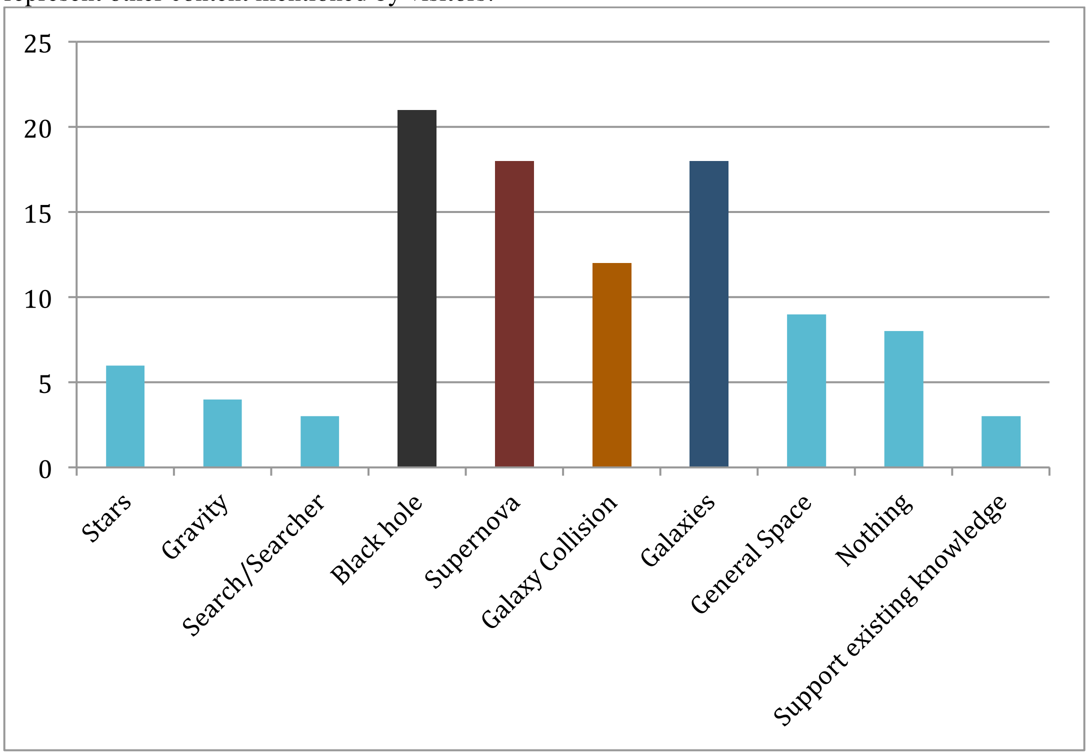
Research Question 3: Visitors and visualizations

While it appeared that the planetarium was meeting its affective goals with the new planetarium shows, I wanted to know what visitors were taking away from the show in terms of cosmology content, and whether there were any patterns revealed in what visitors noticed and understood.

Visuals trump narration every time

My first result from the drawings and surveys was that visitors were articulating the science content in embedded in the visualizations far better than they were remembering and articulating science content from the narration. One open response question asked people what they had learned from the first show produced for the new theater, which had the science fiction plotline. The most popular responses corresponded directly to the four main show visualizations, indicating the impact of these visualizations on the audience. The narrator spoke of other things, and simulated stars and science fiction worlds appeared on the screen, but people reported learning the most about black holes, supernovae, galaxy collisions, and galaxies. Figure 21 graphs the number of mentions of particular content from the first show in on-the-floor and online surveys that asked participants “what did you learn from the planetarium show?”

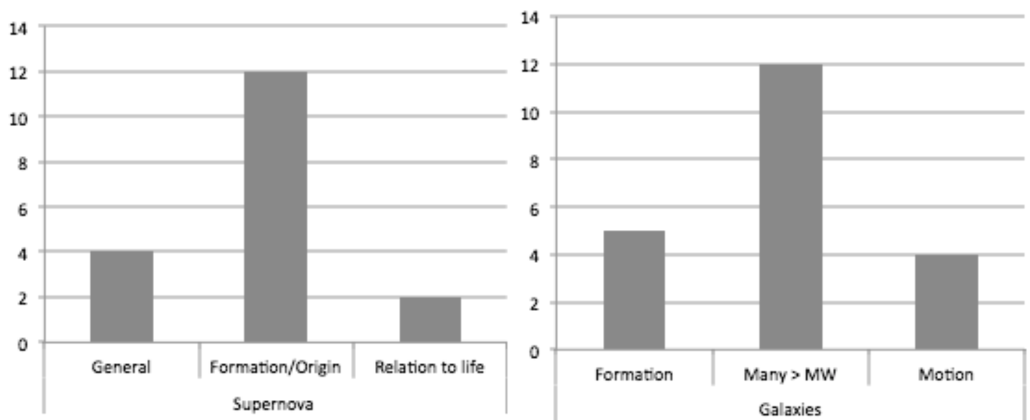
Figure 23. Visitor responses to what they learned from the planetarium show. The four bars in the center represent the content treated in the four major show visualizations, while the light blue bars represent other content mentioned by visitors.



Supporting this result are people's long answer descriptions of what they learned about particular aspects of the Universe, shown in figure 22 below. It turns out most people who mentioned supernovae referred to their origin or why they happen. The origin of the supernova was the focus of the visualization even though the narrator spoke only about the supernova's relationship to life, and about gamma rays destroying a planet. Similarly, most people who mentioned galaxies came away remembering that they had learned that there were many galaxies, not just the Milky Way. Again, this was the most striking aspect of the visualization, although the narrator spoke of dark matter, gravity, and the "cosmic backbone" during this part of the show. He never said anything about there being many galaxies. In figure 22 we see that visitors were 100% more likely to articulate the formation of supernova, expressed visually, than one of the topics treated in the narration. Similarly, visitors were 30% more likely to articulate that there are many galaxies in the Universe, expressed visually, than one of the topics treated in the narration. This implies that not only are people being impressed by scientific visualizations, but when they are asked to go back to those visualizations after the show, they remember their visual content *more* than the narration.

Figure 24. Visitor responses to what they learned about various content in the show. Visitors were 100% more likely to articulate the formation of supernova, expressed visually, than one of the topics treated in the narration. Similarly, visitors were 30% more likely to articulate that there are many galaxies in the Universe, expressed visually, than one of the topics treated in the narration.

.

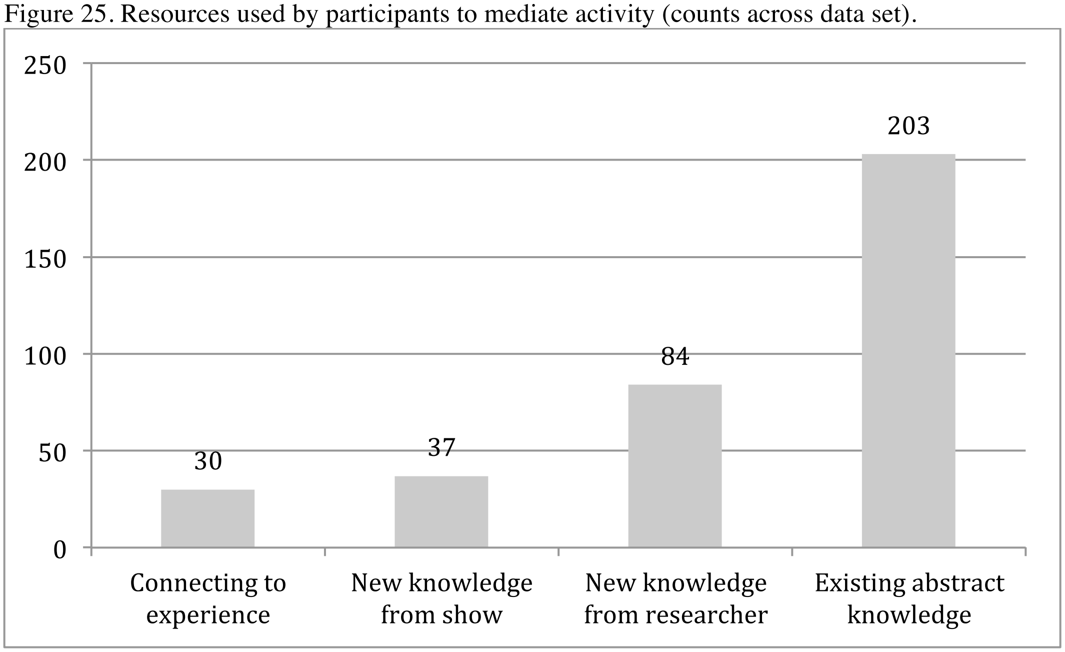


In other words, visitors recreated and expressed visuals (depictive visualizations) rather than individual "facts" that they learned (descriptive visualizations) in their drawings and explanations. They were describing dynamics and images, rather than concepts. This indicates that when re-constructing the experience, the visitors were transforming the conceptual visualizations depicted in the show into perceptual visualizations. This speaks to the potential of the medium as a learning tool: the show gave visitors an opportunity to experience phenomena in a way that allowed them to understand the dynamics and structure of those phenomena, even if they did not pick up the vocabulary or storyline presented by the narration. This lends support to my results from chapter two, where I showed how community college students are picking up important thinking patterns related to cosmological literacy using visualizations, even when they do not use scientific vocabulary.

Prior knowledge makes the difference

From my interviews, I found that visitors are drawing on multiple resources to explain, describe and ask questions about the visualizations. I identified several types of resources, the most common being knowledge provided by the researcher in response to questions, and existing knowledge. Figure 25 shows the proportion of all families I interviewed in the SVL who were relying on various resources to mediate their sense-making.

Figure 25. Resources used by participants to mediate activity (counts across data set).



In particular, families were relying heavily on what they already knew about astronomy in order to explain the visualizations, whether what they already knew led them to the scientific conclusion or not. Here is an example of a visitor drawing from his own knowledge:

> Man: I'm seeing two or three stellar nurseries right now, this would probably have been at the early stages, the later stages of the big bang, possibly

My analysis of the visitor interviews showed that those visitors who, like the man in the quote above, were drawing on more of their own resources to interpret the experience, rather than being guided through by the narration, were more likely to make sense of the visualization in scientific ways (corresponding to a score of 3 on the rubric of scientific accuracy). This meant that those visitors whose co-constructed visuals and explanations that were most relevant to the scientific visuals and explanations offered in the show also had the highest counts of drawing on resources outside the museum context, including space vocabulary not used in the show. This correlation was significant, with a chi-squared probability (p) of $p=0.027766969$, meaning that there is a 2.7% chance that the relationship between prior knowledge and scientific interpretation of the visualization is by chance. Chi-squared probability of less than or equal to 0.05 is commonly taken as justification for rejecting the null hypothesis. This suggests that what traditionally is evaluated as "successful" behavior in the museum (articulating the scientific content of exhibits) is more strongly tied to the resources that visitors are already bringing to the table.

One positive implication of this is that having the opportunity to interpret and process an experience within the family, rather than being guided through step by step, is more true to the kind of experience sought out at places like aquariums, where the big attraction is the fish, not the interpretive plaques or lectures. This kind of experience might actually open up planetarium content for visitors who are intimidated by the content. Institutions that are seen as less "intellectual" and more "experience" driven tend to attract a more diverse audience, particularly in terms of education level.

Another, less optimistic implication of my results is that visitors who do not come to the museum with a background in astronomy, and are not acculturated to interpreting these kinds of experiences, might be at a disadvantage when it comes to traditional definitions of "successful" exhibit interactions. Those people who had resources were making sense of the material in a way that aligned with scientific explanations, while those who came without previous knowledge were not. This implies that those who have resources are still being served by the switch to affective goals, while those who did not have the right knowledge and experience are still not being given the tools necessary to orient their activity toward making sense of the visualization in a scientific way.

A Dangerous Discourse

In this section, I would like to synthesize some of the data from this chapter in a different way, in order to illustrate how and why the discourse around affect can be dangerous. Recall that in the positional map in Figure 21, by far the most often expressed position was that of fulfilling responsibility to visitor experience by meeting affective learning goals. A member of the education department explained that:

> "I have actually changed my philosophy a bit on museum education since I have been here -much more I think now on the affective and personal side of the learning equation, rather than on the conceptual side of the learning equation. You know the average of the stay time at any given floor interaction is about 48 seconds, which you are not going to get meaningful conceptual change – but you can reinforce…you can do some affirmation, you can provide a family kind of feel good message about science."

This position was not exclusive to educators. An animator on the original science fiction show summarized it this way: "It's like you shouldn't try to teach people the subject because you only have them for a limited time, you should teach them to be interested in the subject instead." What this implies is that there is content learning, which takes time, and then there is affect, which is something that can be done quickly. I would argue that changing someone's personal and emotional relationship with science is if anything a more complex process that will take longer than content acquisition. But more importantly, this discourse implies that affect is the opposite of learning, and that this decision to study affect was a shift away from content, toward something more amorphous, related to excitement and curiosity. The following quotes illustrate this position well:

- “The learning more wasn't so much the thing it was more I want it to be fun… for instance there aren't any learning objectives in the show. It's not like I have to learn the galactic center has a black hole.” (astronomer/consultant)
- “It's more intended to get people interested and curious than it is to teach content and that was kind of very explicitly part of the planning and structuring of the show.” (leader in the education department)
- “We don't have to keep forcing people to know like how the science works…I think you need to approach people in a way when they are naturally curious and you awaken that sense of wonder.” (show writer)

The staff defined affect as something related to excitement, as in the following quotes:

- “I see it more as a sharing aspect that sharing the excitement of what's going on and sharing the excitement of this new aspect of the universe” (visualization/consultant)
- “I think the reason why I love the informal science education …we excite people about stuff…and then that opens them up to where they might go back and do it themselves.” (astronomer/consultant)
- “A lot of times when we do a Planetarium show, you set out specific educational objectives…[but this time]…we viewed this environment and this show as more of an inspirational piece. We really wanted people who

came to the planetarium to be sort of awestruck and inspired by what they saw" (animator)

This is an admirable turn away from a single-minded focus on content, and showcases a flexibility inherent in informal settings that is not possible in the traditional classroom. The other theme around defining this notion of affect was curiosity:

- "You're encountering these really exciting things and you're not given a lot of background on them, and any curious person would want to know more." (producer/astronomer)
- "You want everybody to feel positive and affirmed and get some content and get a good attitude and maybe even want to learn a little bit more when they go home." (astronomer/consultant)

The planetarium staff expressed this idea that by sharing amazing stuff about the Universe, eventually content acquisition would happen, *at least for some people*, which becomes a euphemism for the same people who have always been seen as successful in museums, those people who have always interacted with the exhibits in expected ways. Notice that this is effectively shifting the burden for learning off of the planetarium…any curious person would want to know more, if they *want* to learn it, they will. It can be a very dangerous one when we start to blame people for not conforming to mainstream indicators of learning, as in the following quotes:

- "I think people learn the best when they want to, you can't make anyone learn something, and you can give the clearest explanation of stuff and…if they're not in the mood to absorb any of the material they're just not going to…" (astronomer/consultant)
- "There is a certain space awareness, you know, maybe it's people who are genuinely interested…I think that you have a hard core constituency of people who like really believe like this is important." (show writer)

As I mentioned earlier, these quotes echo a dominant deficit discourse in education around kids who "just don't want to learn," and it is most often applied to children from diverse cultural and linguistic backgrounds (Kohli, 2009; Gorski, 2008), shifting blame for unmet expectations away from institutions failing to meet the needs of diverse populations (Kozol, 1988; Oakes, 2005), and onto diverse learners. This is usually what happens when we put pressure on an institution to meet mainstream goals, is that those people who are not aligning with this mainstream definition of success get blamed for it.

The planetarium staff associated this shift toward affective goals with expanding access to content. There was a sense throughout the interviews that if we shift our focus away from science content, then more people will be interested in coming – a conflation of affective goals with outreach and broadening access. This quote says it succinctly:

> "Something that all the museums get slammed for all the time, and rightly so, but there is a feeling that it's for, you know, the white kids from…the suburbs

> not, you know, the kids from the neighborhoods. So there is a lot of – there has been some change from kind of strain on conceptual development to working more on that kind of affective side and we work with teachers and still do content reinforcement, but we also always kind of work that empowerment side and the affective side" (leader in the education department)

What she is saying is that the shift toward affective goals is in fact an effort to make museum attendance more diverse. The message in this quote is that the kids from the neighborhoods, a euphemism for low-income students of color, would rather not learn science - those students don't "want to learn." This quote illuminates the line where the discourse around affect becomes dangerous. Despite all good intentions, this is a racist, classist impulse, which manifests itself in larger political conversations and institutional patterns, encouraging a "perpetuation of institutional values and relationships that safeguard dominant power structures" (Darder, 1991, p 4).

Conclusion

Expansive Learning

Adler is going through an expansive learning cycle, learning from its own contradictions, resulting in a shift away from traditional museum objects, toward the historically new, elusive object of audience "affect." But does this object overlap with that of the museum visitors? Visitors are multi-voiced – they come to the Adler for many reasons, but what emerges as a primary object for visitors from all backgrounds is that of the astronomy content. Visitors love the immersivity of the visualizations, and they have a lot of potential for supporting cosmological literacy due of their ability to provide complex content and an engaging experience without high linguistic demand – even mainstream visitors are focusing more on the visuals than the narration. But it is important to note that astronomy content is high on the list of what visitors orient their activity toward at the Adler.

So are visitors still learning the content from visualizations even though Adler is not prioritizing this object? The answer is sometimes – particularly if the visitor is able to bring the resources of existing content knowledge and experience to the activity. Those visitors who were able to apply existing and complex domain knowledge and experience to their drawings and interviews were more likely to interpret the visualizations scientifically, while those who were being exposed to the planetarium content for the first time were lost. If visitors who are well-resourced are still learning the content, even if the museum says the content is not important, we are simply shifting accountability away from the museum to meet the needs of those who are not meeting those objectives. In other words, assessment oriented toward affective goals is too blunt an instrument to pick up on lingering disparities between museum experiences. If we want to hold ourselves accountable, we need an instrument that is sensitive to disparities, and reveals when certain knowledge and resources are being heavily privileged. We should start with learners from diverse cultural and linguistic backgrounds, whose voices will otherwise get lost in the statistics, since they simply aren’t attending the museum right now.

The fact that those visitors who drew on their own prior experience and knowledge resources had an easier time reconstructing their experiences could be attributed in part to more prior research and knowledge of the content. But it could also be due to a fundamental belief in the relevance of one's own experience. If a visitor does not see the content in the planetarium as relevant to their own experience, or their own experience as relevant to figuring out science, then perhaps they will be less willing to draw upon their own resources to engage in activity. Connecting science to learners' everyday context, what they see and experience in their communities, makes the content accessible for culturally and linguistically diverse students (Stoddart, Solis, Tolbert, & Bravo, 2010) allowing these students to find a place for themselves in science (Bouillion & Gomez, 2001).

Implications

In our conversations about students, and in the way that we frame research, we always need to be aware of how we are contributing to, or disrupting larger discourses on race, gender, citizenship and sexuality, among other things (Darder, 1991; Moschkovich, 2011). We cannot talk about equity as dumbing things down. This is not broadening access.[33] We need to sart with visitors, and not just the visitors

[33] The very idea of broadening access needs to problematized, rather what we need to be doing is exploring "multiple ways of knowing and doing science that are reflective of the social, historical,

that are already there, because this perpetuates these cycles of access. We should start with learners from diverse cultural and linguistic backgrounds, whose voices will otherwise get lost in the statistics, in order to diversify the voices of people who are being heard, of people who are making decisions, of people who are judged as successful museum-goers off which we should base our standards.

Visualizations need to be studied within a sociocultural context, and retaining data on race/ethnicity, SES and education level of those visitors interacting with them. Learning, especially in complex sites like planetariums, is multifaceted, and has both affective and cognitive outcomes, and this is good. Learning is multidimensional which is important in an age when accountability is key (Hooper-Greenhill, 2004). The visualizations clearly have an effect on people; they are excited, and they are learning. However, if those visitors with resources are leaving the planetarium show with consistently different outcomes than those visitors without, even if on average quantifiable show goals being met, this is a problem. This means that people are extracting different forms of capital from the same exhibits, and indubitably those forms of capital being extracted by the White, well-educated visitors will be more socially valuable in the mainstream.

---

and political context in which science has been constructed and in which students learn that science" (Barton, 1998, p. 4).

I argue that quantifiable accountability is not necessarily what informal institutions need to strive for, rather they need to make sure they are being held accountable to visitors, and in particular museum visitors who are not being served, those who are not acculturated to the planetarium, and do not come with a background knowledge of astronomy. This requires more than just "targeting" diverse populations like outreach programs, but rather including the voices of culturally and linguistically diverse families in museum design and practice, including decision-making bodies. While both content and affect are vital, we need to think critically about how we are serving or not serving learners, rather than focusing on making and meeting arbitrary standards, and we can't do that if we are blunting our instruments.

The emphasis on standardized assessment of learning outcomes limits our ability to accurately gather data about individuals outside the cultural and linguistic mainstream (Solano-Flores & Nelson-Barber, 2001). Neither the information being assessed (Latour & Woolgar, 1979; Lemke, 1991) nor the form in which the assessment takes (Solano-Flores, 2008; Moschkovich, 2007; Gipps, 1999) is culturally or linguistically neutral (Shaw et al., 2010). Just as it is a mistake to assume that science is objective and unbound by social context, so too are assessments socially and culturally situated (Gipps, 1999), and inextricable from language and linguistic development (Solano-Flores, 2008). According to the Standards for Educational and Psychological Testing, ''for all test takers, any test that employs language is, in part, a measure of language skills,'' (American

Educational Research Association [AERA], American Psychological Association [APA] & National Council on Measurement in Education [NCME], 1999, p 91). Thus if we want to make sure we are serving all learners at the museum, evaluation needs to be multifaceted, multimodal and multilingual.

Conclusion: Implications, recommendations and next steps

In the conclusion to my dissertation, I begin by summarizing my results. I then discuss implications for instruction and visualization design, providing recommendations based on my results.

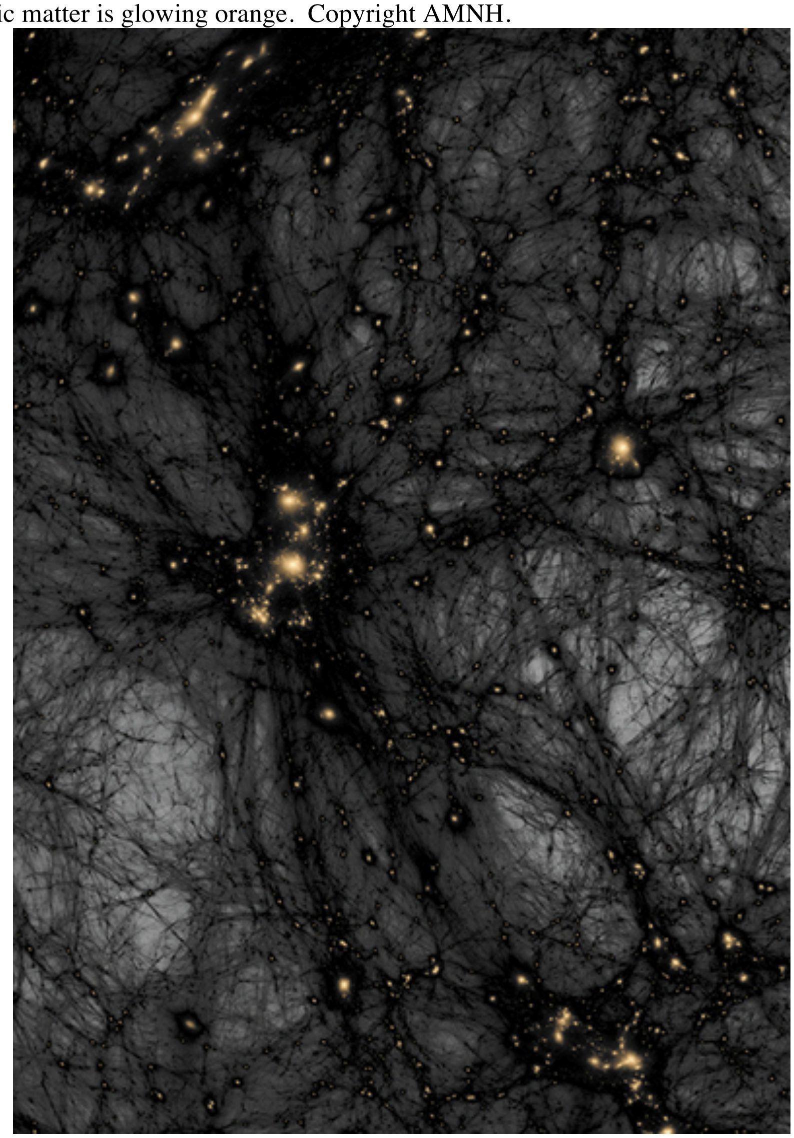
Summary of Results

In the previous chapters, I looked at cosmology visualizations and learning from three very different methodological perspectives: 1) investigating how visual cues embedded in a visualization mediate learners' interpretation of cosmology content; 2) investigating the object-oriented activity of culturally and linguistically diverse learners in making sense of a visualization; and 3) investigating shared objects in a dynamic network of activity systems oriented toward and mediated by visualizations at a planetarium.

In the first chapter, I revealed that visual cues like color can have a significant effect on how learners interpret a visualization, lending credence to the first-generation activity theory assumption that context and mediation matters. Respondents who saw the original version of the CLUES visualization, which used white to indicate dark matter and blue to indicate empty space, were almost four times more likely to misidentify dark matter in the visualization than those who saw a version of CLUES where dark matter was indicated by a color that was darker than the background. Respondents who saw the original version of CLUES were also only half as likely as other participants to correctly indicate that there were no stars present in the visualization. This finding that dark matter is best represented as dark may seem simplistic, but it has already made ripples in the planetarium show production world, and my work is credited in the groundbreaking new "Dark Universe" planetarium show produced by the American Museum of Natural History (AMNH) in collaboration with the California Academy of the Sciences (AMNH, 2014).[34] The show has been very well received, and Dennis Overbye of the New York Times chose to highlight the dark matter visualization (shown in Figure 26) specifically in his review: "One sequence, shown entirely in black and gray, shows tendrils of dark matter snaking across the sky, connecting and growing into a web, while sound effects that seem right out of a Harry Potter movie play in the background. These dark tendrils will form the cradles where stars and life will eventually form" (Overbye, 2013). Curator Mordecai-Mark Mac Low of AMNH pointed to the dark matter visualization as his favorite part of the show, telling SPACE.com that "it's such a great visualization…the actual effort to do that using a novel algorithm and a novel visualization method is just a high point for me" (Kramer, 2013).

[34] Mark SubbaRao of the Adler Planetarium shared my results with Carter Emmart of the American Museum of Natural History, director of the Dark Universe show, during a planetarium conference. Based on this information, Emmart chose to illustrate dark matter as a dark color on a light background as shown in Figure 26, despite recommendations from technological consultants that the background be dark so as to better take advantage of projection technology.

Figure 26. Still from "Dark Universe" illustrating dark matter as black on a white background. Baryonic matter is glowing orange. Copyright AMNH.



In the second chapter, I shifted the focus of analysis away from specific mediational cues within the visualization, to the learners themselves, and the second-generation object-oriented activity system. I introduced a drawing activity to serve as the improvable object for activity, and found that it supported learners in cosmological sense-making around the content of the visualization. I found that students were noticing and theorizing about the visualization using hybrid language, (everyday/scientific and Spanish/English). The low linguistic demands of the visualizations allowed the students to engage directly with the content, using powerful tools like visual analogies, both attributional and relational, to discuss and refine their understanding of the system.

In chapter three, I used Engeström's (2001) framework for third-generation dynamic networks of activity to reveal historical contradictions in activity at the Adler Planetarium. First, a contradiction emerged between the historical role of the planetarium and the pressure to conform to more experiential institutions of science learning. This contradiction manifests itself in the perceived divide between curators and educators, which echoes a second, less inchoate contradiction between a responsibility toward accuracy, and a responsibility toward experience, one that coexists within individuals, but definitely has loci within the education and astronomy departments. I then looked to interview data to show the ways in which these contradictions have manifested themselves in an expansive learning cycle that has resulted in the formation of a new shared object at the Adler, one that centers around the discourse of "affective" learning, rather than the acquisition of science content. I also found that visitors largely enjoyed the experience of the non-traditional, visualization-driven planetarium show that emerged from this discourse. They felt immersed, like they were "experiencing space." This is an important point when we look at the competition for such institutions, like aquariums. Aquariums present fish in a way that cannot be experienced by visitors at home, or arguably even in the ocean. At the planetarium, this kind of experience is almost impossible due to the fact that the institution is open during the day (so telescopic observation of objects other than the Sun is not viable), and the extreme distances of the phenomena under consideration. When I looked at visitor data, however, a troubling and familiar pattern emerged. Visitors who were able to apply existing and complex domain knowledge and experience to their drawings and interviews were more likely to interpret the visualizations scientifically, while those who were being exposed to the planetarium content for the first time were lost. If visitors who are well-resourced are still learning the content, even if the museum says the content is not important, we are simply shifting accountability away from the museum to meet the needs of those who are not meeting those objectives. In other words, assessment oriented toward affective goals is too blunt an instrument to pick up on lingering disparities between museum experiences. If we want to hold ourselves accountable, we need an instrument that is sensitive to disparities, and reveals when certain knowledge and resources are being heavily privileged.

Implications for Instruction

Visualizations have the potential to foster cosmological literacy because they are modeling large-scale systems in a way that is not necessarily linguistically intense, and support students in engaging in sense-making associated with cosmological literacy. But specific cosmological concepts could get lost if there aren't additional scaffolds or supports provided – don't rely on narration if it is key that people know the components. The vocabulary needs to be scaffolded. It is important to remember that even if the vocabulary doesn't come naturally to students, they may still be learning if we listen past their English and/or scientific fluency.

Cosmological literacy as I have defined it is more fundamental than the memorization of vocabulary. My community college participants used resources like hybrid language and analogy to make sense of visualizations, so these strategies should be supported and guided by teachers whenever possible, introducing new vocabulary when appropriate. In addition, providing an improvable object such as drawing in order to facilitate sense-making activity could be a good idea. While immersive experiences can be hard to simultaneously scaffold through instruction, the development of cosmological literacy can be supported afterward through the introduction of an improvable object that encourages cosmological sense-making. Create opportunities after the visualizations for learners to process with other learners, either through presenting questions, or through a drawing activity. This might be trickier in planetarium settings, but is not impossible.

Right now, discourse at the Adler has shifted to affective goals, but it is unclear whether this will serve diverse visitors, who still want to learn from materials at the planetarium, but may not always have the resources necessary. An emphasis on affective goals effectively excuses the planetarium for serving some visitors better than others. My recommendation would be to include diverse learners in the cycle of visualization development, as the Adler did when they changed the way they showed dark matter based on my results in Chapter 1. It is vital to always be self-reflexive and critical, but in order to do this we need instruments that are sensitive to disparities between visitors from diverse backgrounds.

Implications for Visualization Design

Even what seem like the smallest details matter in visualization design – we cannot neglect things like color and form. In order to guide our decision making in terms of how to provide visual cues for learners, we need to make sure we are including the voices of learners in research and development - bringing in learners from all backgrounds to evaluate what works and what doesn't. This is important because it can increase the potential audience at informal astronomy institutions, but also because it broadens access to the content embedded in the visualizations, which is vital if we want to break cycles of inequitable access in science. For culturally and linguistically diverse learners in particular, qualitative data is important to facilitate listening past English fluency (Moschkovich, 2002; 2006; 2008), so we should be establishing research protocols for the development of visualizations that go beyond surveys to see what learners are actually doing.

In creating narration for visualizations, don't shy away from hybrid language and imperfect analogy. People were turned off to the narration when it was unfamiliar to them, and cling to metaphor and analogy. Keep in mind though that the major concepts that learners come away with are those that can be presented visually. If there is a learning outcome in mind for the visualization, the concept should be expressed in the visual as much as possible.

A final implication for visualization design is fairly straightforward: make them immersive whenever possible. This can be done better in informal settings. Immersivity gets people engaged and provides a unique experience with low linguistic demand. Visualizations have the potential to provide a unique sensory experience for learners, an engaging and beautiful tool that exposes them to complex scientific content about the wonders of the Cosmos, both visible and invisible, without requiring them to be already fluent in the language of science. If we are thoughtful in how cosmology visualizations are designed and used, I think that they can change the way learners think about and understand our Universe, opening pathways to participation in cosmology, and expanding cosmological literacy.

Appendix A – CLUES Survey

BEFORE YOU BEGIN, WE WOULD LIKE YOU TO LOOK AT A SHORT COSMOLOGY PRESENTATION. THIS SHOULD TAKE LESS THAN 5 MINUTES, AND INCLUDES A VISUALIZATION AND SOME ACCOMPANYING TEXT. PLEASE WATCH THE VIDEO BELOW FROM START TO FINISH, AND READ THE DESCRIPTION BELOW IT BEFORE MOVING ON. YOU WILL NOT BE ABLE TO RETURN TO THIS PAGE ONCE YOU HAVE LEFT.

In the visualization above, starting just after the Big Bang, the laws of nature are at work. The same force that keeps you grounded on Earth and stops you from flying off into space—gravity—is pulling dark matter together, shaping the cosmic web, an invisible pattern that will dictate the large-scale structure of the galaxy distribution. This is the spine of our universe. Starting from random ripples: Dark Matter and Dark Energy are shaping the cosmic backbone. Over billions of years, dark matter matter is pulled into immense, massive filaments, strengthening the web. Smaller clumps of Dark Matter are formed as well, and inside of these, although we cannot see them here, galaxies form.

In the visualization, we first see the formation and evolution of the cosmic web. Then we travel through this invisible cosmic web, toward the Virgo Supercluster, home to our Milky Way Galaxy.

1. What answer best describes your gender?

- ○ Male
- ○ Female
- ○ Intersex
- ○ Questioning

2. Please choose the answer that best describes your education level.

- ○ I have not graduated from high school or the equivalent.
- ○ I have a high school degree or equivalent.
- ○ I am currently in a 2 year associates degree program, or 2 year transfer program.
- ○ I am currently in a 4 year bachelors degree program.
- ○ I hold a bachelors degree.
- ○ I hold one or more doctoral degrees (MA, PhD, EdD, etc)

3. Is English your first language?

- ○ Yes.
- ○ No.

4. With which ethnic background do you most closely identify (you may check more than one answer if it applies):

- ☐ Hispanic/Latino
- ☐ Black
- ☐ White
- ☐ Asian/Asian American
- ☐ Pacific Islander
- ☐ Native American/American Indian/Alaskan Native
- ☐ Multiracial
- ☐ Other (please specify)

5. Have you ever been diagnosed as color blind, or do you suspect yourself to be colorblind?

- ○ Yes
- ○ No

6. How likely are you to read about, watch or listen to astronomy content outside of what is required for school?

- Very likely.
- Somewhat likely.
- Not very likely.
- Not at all likely.

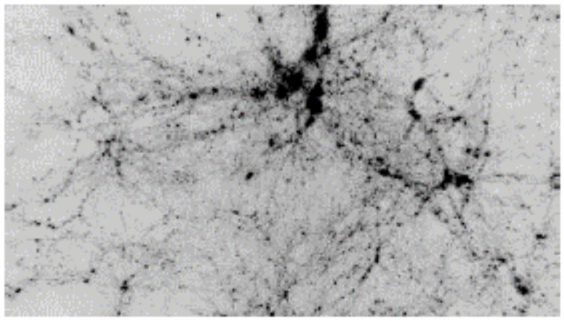
7. Please answer the following questions as best you can, or mark "I have no idea."

	Yes.	No.	I have no idea.
Most plants get their energy from the Sun.			
Jupiter is the largest planet in our Solar System.			
Lithium is the lightest element in the periodic table.			
An object's gravity is determined by its mass.			
Our Sun is the largest star in the galaxy.			
An object's acceleration is always equal to its speed at any given moment.			

8. Did the visualization in the cosmology presentation look familiar to you?

- Yes.
- No.

The following image is a still frame taken from the visualization in the cosmology presentation, provided for reference.



9. Please describe what you saw in the cosmology presentation.

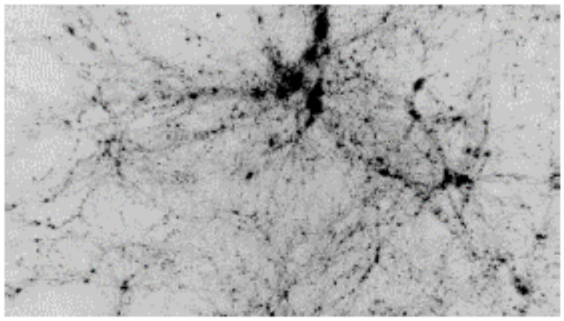
10. What part of the Universe was being depicted in the cosmology presentation?

11. When did the events shown in the visualization in the cosmology presentation take place? Please choose the best answer.

- In the moments immediately after the big bang.
- Continuously from the moments immediately after the big bang until the present day.
- Within the last million years.
- They have not taken place yet.

12. How is gravity involved in the events shown in the visualization in the cosmology presentation?

The following image is a still frame taken from the visualization in the cosmology presentation, provided for reference.



13. Using what you remember from the cosmology presentation, what color is the dark matter in the image above?

- Black (or dark grey)
- White (or off-white)
- There is no dark matter visible in the visualization.

14. Using what you remember from the cosmology presentation, what color are the stars in the image above?

- Black (or dark grey)
- White (or off-white)
- There are no stars visible in the visualization.

15. Using what you remember from the cosmology presentation, what color is the empty space in the image above?

- Black (or dark grey)
- White (or off-white)
- There is no empty space visible in the visualization.

16. Using what you remember from the cosmology presentation, what color is the hydrogen gas in the image above?

- Black (or dark grey)
- White (or off-white)
- There is no hydrogen gas visible in the visualization.

17. What resources did you draw on the most to answer the questions about the visualization in the cosmology presentation?

- The text that accompanied the video
- My own previous knowledge about cosmology
- Both the text that accompanied the video, AND my own previous knowledge about cosmology
- I just guessed

18. Was there anything in the visualization that confused you? If so, what?

19. Do you have any additional comments about the visualization in the cosmology presentation? If so, please share them here.

Appendix B – Visualization Descriptions

Visualization 1:

Title: Merging Spiral Galaxies

Description: This video shows a simulation of two merging spiral galaxies as they would appear through a telescope, including absorption of starlight by interstellar dust. This movie won a semifinalist honor (top ten in the category) in the 2008 NSF Science & Engineering Visualization Challenge, and was also featured in the National Geographic Special "Inside the Milky Way" in 2010. A high-quality version can be downloaded from http://code.google.com/p/sunrise/wiki/CoolImagesAndMovies. The visualizations is explained and

Narration: (narrated by Joel Primack, and was translated into Spanish by Zoë Buck, in consultation with Eduardo Mosqueda) Spanish translation: "Les voy a mostrar un video elaborado por mi equipo. Representa una fusion entre galaxias que son similares a la Via Lactea y la Galaxia Andromeda Son imagenes realisticas y de color. Cuando se funden dos galaxias asi, provocan "arranques estelares" gigantes, que son la formacion de millones de estrellas nuevas (que parecen azules en las imagenes). Pero el polvo, (que parece anaranjado en las imagenes) absorbe noventa por ciento de la luz, especialmente durante la formacion estelar y irradia otra vez la energia en longitudes de onda larga y invisible. Les voy a mostrar simplemente como aparecerian las galaxias en el telescopio de Hubble. Aqui hay una galaxia, que puede ser la nuestra. Y ahora ponemos las cosas en marcha, hacia la otra galaxia, que puede ser la galaxia Andromeda. Mientras se cruzan las galaxias, la interaccion gravitatoria entre las dos provoca un "arranque estelar" gigante. Mira cuantas estrellas que se acaban de formar, en azul. Gravedad se jala las galaxias asi mismas. Se funden los centros, y ahora las estrellas que rodeaban las galaxias en la forma de un disco, ahora forman una bola gigante de estrellas- una galaxia eliptica. En total, el proceso dura aproximadamente dos mil millones de anos. Ya termino, y estamos dando una vuelta con la camara alrededor de la galaxia eliptica. Hay una via de polvo a punto de cruzar nuestro campo visual. A veces vemos estas vias de polvo en galaxias elipticas que observamos por telescopio."

Credit: Patrik Jonsson, Greg Novak & Joel Primack, University of California, Santa Cruz.

Visualization 2:

Title: Making Galaxies (excerpt 4:40- 6:40)

Description: An Advanced Visualization Laboratory at NCSA and Space Visualization Laboratory at Adler Planetarium Joint Production. The video excerpt shows a fly through of Sloan Digital Sky Survey galaxies made by Miguel Angél Aragón Calvo and Mark Subbarao. After this the video shows the non-linear evolution of the Universe made by the Advanced Visualization Laboratory.

Narration: The narration was written by Mark Subbarao, and narrated by Shera Street.

2D: http://svl.adlerplanetarium.org/downloads/MakingGals_800.mov

3D and Spanish: http://svl.adlerplanetarium.org/astroviz/makinggalaxies.html

Visualization 3:

Title: Constrained Local UniversE Simulation (CLUES)

Description: This video is a visualization of CLUES, simulating the evolution of the large-scale-structure of the local universe. The first 30 seconds shows the evolution of the simulation to present day, followed by a fly-through of the present day local universe. This visualization is actually a low-resolution square version of the visualization that was featured in 2011-12 as the opening segment of the first show at the Adler Planetarium's new dome: "The Searcher." A modified version of the script from this show was read over the visualization.

Narration (modified from the script by Nick Sagan): **"**Right after the Big Bang the laws of Nature are at work. The same force that keeps you grounded on Earth and stops you from flying off into space—gravity—is pulling matter together, shaping a pattern. Like a cosmic spider's web. Around you is the spine of Our universe. Starting from random ripples: Dark Matter and Dark Energy are shaping the cosmic backbone. We are traveling through the cosmic web towards the Virgo Supercluster home to the Milky Way Galaxy. Over billions of years matter is pulled into immense, massive filaments, strengthening the web . Smaller clumps of Dark Matter are formed as well, and inside these galaxies form."

Credit: Stefan Gottloeber (Astrophysics Institute Potsdam), Anatoly Klypin (New Mexico State University), and Nina McCurdy and Joel Primack (UCSC), visualization by Chris Henze (NASA Ames Research Center).

Appendix C – Community College Interview Protocol

First I would like to thank you for participating in this research. In addition to teaching at Hartnell, I am also a student at the University of California, and I am writing my dissertation on how students learn about astronomy using visualizations.

I'm taping today's discussion, so that I have an accurate record, but the video will remain confidential and will be seen only by University of California researchers. Your participation is voluntary and confidential, and you may choose not to give a response to any question asked. Nothing you say will ever be reported or made public in any way that could identify you, and nothing you do or say today will impact your performance in the class in any way. Because we are taping this, I may ask you to repeat a comment. Also, I may ask for your response if you have not had a chance to share. Does anybody have any questions at this point?

Okay, great. I'd like to start by asking you to take a few seconds to sign the consent form I have passed out, which says that your participation is voluntary and confidential.

(Pass out consent form)

I am going to play you a short clip about the Universe. (play visualization[s]).

1) What were your general impressions of the visualization?
2) I have a blank piece of paper. Please work together to draw what you learned from the visualization (move to other side of room, type on computer, give group at least five minutes before checking in, let them take as much time as they need).
3) Please explain this drawing. What is it a drawing of? Why did you choose to draw what you did?
4) What questions do you have about this visualization that you might want to explore further?

Thank you for your participation.

Appendix D – Planetarium Interview Protocols

Focus Groups

First I would like to welcome you and thank you for participating in this research. My name is Zoë Buck, and I do not work for the Adler. I am an astrophysics education researcher from the University of California, and I am interested in how people like you are interacting with the Searcher show.

I will be showing some visualizations from the show, and asking you to talk about them, and about the show. I will also ask you to share the questions that came up for you about the science in the show, and see if I can answer some of them. I'm taping today's discussion, so that I have an accurate record, but the video will remain confidential and will be seen only by University of California researchers. Your participation is voluntary and confidential, and you may choose not to give a response to any question asked. Nothing you say will ever be reported or made public in any way that could identify you. I want to know what you think and what your opinions are-both positive and negative-and of course, you are the experts on that. At the end of the discussion, I will be passing out gifts to thank you for your participation in this research. Remember that I want you to be as honest and straight forwards as you can. Because we are taping this, I may ask you to repeat a comment. Also, I may ask for your response if you have not had a chance to share. Does anybody have any questions at this point?

Okay, great. I'd like to start by asking you to take a few seconds to sign the consent form I have passed out, which says that your participation is voluntary and confidential, and then answer the demographics questions on the next page.

(Pass out survey and consent form)

1) What were your general impressions of the show?

2) I am going to play a clip from the show for you. Please watch. (Play CLUES)

What are your general impressions of this clip? Do you feel like you could explain what is going on in this clip to a child or a friend? How? Could you have explained this before seeing the show?

What questions do you have about this clip that you might want to explore further?

3) (Do this again for other visualizations)

4) What were your general impressions of the story told by the narrator about his search?

5) After seeing the show, what other questions do you have?

Family Interview in SVL

First I would like to welcome you and thank you for participating in this research. I am an astrophysics education researcher from the University of California, and I am interested in how people are interacting with activities like the one you just used.

I'm taping today's discussion, so that I have an accurate record, but the video will remain confidential and will be seen only by University of California researchers. Your participation is voluntary and confidential, and you may choose not to give a response to any question asked. Nothing you say will ever be reported or made public in any way that could identify you. I want to know what you think and what your opinions are-both positive and negative-and of course, you are the experts on that. Because we are taping this, I may ask you to repeat a comment. Also, I may ask for your response if you have not had a chance to share. Does anybody have any questions at this point?

Okay, great. I'd like to start by asking you to take a few seconds to sign the consent form I have passed out, which says that your participation is voluntary and confidential.

(Pass out consent form)

I am going to play you a short clip about the Universe. (play visualization[s]).

5) What were your general impressions of the visualization?
6) I have a blank piece of paper. Please work together to draw what you learned from the visualization (move to other side of room, type on computer, give family at least five minutes before checking in, let them take as much time as they need).

7) Please explain this drawing. What is it a drawing of? Why did you choose to draw what you did?

8) What questions do you have about this visualization that you might want to explore further?

Thank you for your participation.

Family Interview on the Floor

Did you just see the planetarium show? (If yes) – I am a researcher from the University of California, Santa Cruz. Would you like to participate in a short activity that may be used for research purposes? The activity should be done as a family, and will take approximately 5 minutes. Afterward, you may choose any of the souvenirs that I have on display to take home with you.

I have here a short survey that should be filled out by an adult. Then on the next page, I ask you to draw what you learned from the show. This activity you can do together as a family. Finally, on the last page please explain what you drew.

(When they bring me the completed survey) – tell me about that experience? What did you draw? Why?

Adler Institutional Protocol

I'm taping today's discussion, so that I have an accurate record, but the video will remain confidential and will be seen only by University of California researchers. Your participation is voluntary and confidential, and you may choose not to give a response to any question asked. Nothing you say will ever be reported or made public in any way that could identify you. Do I have your permission to record?

Start by telling me your name, and your position.

How did you get involved with the Adler?

What was your role in the development of this show?

How do you think people learn best?

Given this, what is the best way to teach?

Do you think that visualizations are more effective than other forms of instruction? Why or why not?

Do you think Adler has a philosophy on teaching and learning?

What is the philosophy of the Adler on teaching and learning?

Is this philosophy different from your philosophy?

How does this philosophy shine through in this planetarium show?

What do you think should be the primary goals of a visualization in a planetarium show?

What do you think are the primary goals of the visualizations in this planetarium show?

Which of these are educational goals? What makes them educational goals?

Which goals are the most important? Why are these most important?

How does the show address these goals? Could the show address these goals better?

What was your role in the development of educational goals for the show?

Tell me more about the premise of this show. How does this set it apart from other planetarium shows?

Were there any other decisions like these that you were a part of in the making of this show?

How scientifically accurate are the visualizations in this show? How important is it that a show be scientifically accurate?

How important is it that a show be entertaining?

What do you think people will be learning when they leave this show?

How important is it for people to learn about cosmology? Why? What is cosmology? What are the most important concepts in cosmology for people to learn?

Do you think that Adler attracts a population that is representative of the demographics of Chicago? Why or why not?

What does Adler do to address this? What could Adler do to address this? How does the planetarium show address this? How might the planetarium show address this?

REFERENCES

Achinstein, B. and Ogawa, R. T. (2011). Change(d) Agents: New Teachers of Color in Urban Schools. Teachers College Press, 2nd edition. Palen, S. and Proctor, A. 2006, "Astronomy in the k–8 core curriculum: A survey of state requirements nationwide," Astronomy Education Review, 5, 23.

Abrams, N. E., & Primack, J. R. (2011). The new universe and the human future: How a shared cosmology could transform the world. Yale University Press.

Allen, S. (2004). Designs for learning: Studying science museum exhibits that do more than entertain. Science Education, 88(S1), S17-S33.

Amaral, O. M., Garrison, L., and Klentschy, M. (2002). Helping English learners increase achievement through Inquiry-Based science instruction. Bilingual Research Journal, 26(2):213

American Association for the Advancement of Science (AAAS). (1993). "Benchmarks for science literacy," Project 2061, New York: American Association for the Advancement of Science.

American Educational Research Association, American Psychological Association, & National Council on Measurement in Education. (1999). Standards for educational and psychological testing. Washington, DC: American Psychological Association

American Museum of Natural History (AMNH). (2014). *Dark Universe*. Planetarium show produced in collaboration with the California Academy of the Sciences. New York.

Ardac, D. & Akaygun, S., 2004. Effectiveness of multimedia-based instruction that emphasizes molecular representations on students' understanding of chemical change. J. Res. Sci. Teach., 41(4), 317.

Ash, D. (2003). Dialogic inquiry in life science conversations of family groups in a museum. Journal of Research in Science Teaching, 40(2), 138-162.

Ash, D. (2008). Thematic continuities: Talking and thinking about adaptation in a socially complex classroom. Journal of Research in Science Teaching, 45(1):1-30.

Ash, D. (2014). Positioning Informal Learning Research in Museums within Activity Theory: From Theory to Practice and Back Again. Curator: The Museum Journal, 57(1), 107-118.

Ash, D. & Lombana, J. (2013). Methodologies for Reflective Practice and Museum Educator Research. In D. Ash, J. Rahm and L. Melber (Eds.), Research to Practice: Theoretically Informed Methodologies for Doing Research in Informal Learning Settings. Sense Publishers. Rotterdam, the Netherlands.

Austin, J. L. (1962). How to do things with words. Oxford: Oxford University Press.

Bakhtin, M. M. (1986). Speech genres and other late essays (No. 8). University of Texas Press.

Bar, V., Zinn, B., Goldmuntz, R. and Sneider, C. (1994) Children's concepts about weight and free fall. Science Education, 78, 149-169.

Bar, V., Zinn, B. and Rubin, E. (1997) Children's ideas about action at a distance. International Journal of Science Education, 19, 1137-1157.

Bartolome, L.I. (2005). Creating an Equal Playing Field: Teachers as Advocates, Border Crossers, and Cultural Brokers. In Z.F. Beykont (Ed.), The Power of Culture: Teaching Across Language Differences (pp. 167-191). Cambridge, MA: Harvard Education Publishing Group.

Barton, A. C. (1998). Feminist science education. Teachers College Press.

Baxter, J. (1989). Children's understanding of familiar astronomical events. International Journal of Science Education, 11, 502.

Bennett, T. (2005). Civic laboratories: museums, cultural objecthood and the governance of the social. Cultural Studies, 19(5), 521-547.

Bennett, T. (2013). The birth of the museum: History, theory, politics. Routledge.

Berg, T., & Brouwer, W. (1991). Teacher awareness of student alternate conceptions about rotational motion and gravity. Journal of Research in science teaching, 28(1), 3-18.

Bloom, B. S.; Engelhart, M. D.; Furst, E. J.; Hill, W. H.; Krathwohl, D. R. (1956). Taxonomy of educational objectives: The classification of educational goals. Handbook I: Cognitive domain. New York: David McKay Company.

Bødker, S. (1996). Applying activity theory to video analysis: how to make sense of video data in HCI. Context and consciousness: Activity theory and human-computer interaction, 147-174.

Borun, M., Massey, C., & Lutter, T. (1993). Naive knowledge and the design of science museum exhibits. Curator: The Museum Journal, 36(3), 201-219.

Bouillion, L.M., Gomez, L.M. (2001). Connecting School and Community with Science Learning: Real World Problems and School-Community Partnerships as Contextual Scaffolds. Journal of Research in Science Teaching, 38(8), 878-898.

Bourdieu, P. (1993). The field of cultural production: Essays on art and literature. Columbia University Press.

Bransford, J. D., Brown, A. L., and Cocking, R. R. (2000). How People Learn: Brain, Mind, Experience, and School: Expanded Edition. National Academy Press., Washington, DC.

Brown, B. A. (2004). Discursive identity: Assimilation into the culture of science and its implications for minority students. J. Res. Sci. Teach., 41(8):810-834

Buck, Z.E. (2013). The Effect of Color Choice on Learner Interpretation of a Cosmology Visualization. Astronomy Education Review, 12(1).

Buck, Z.E., Lee, H.S., Flores, J. (in press). I'm Sure There May be a Planet There: Student Articulation of Uncertainty in Argumentation Tasks. International Journal of Science Education.

Buxton, C. (1998). Improving the science education of English language leaners: Capitalizating on educational reform. Journal of Women and Minorities in science and engineering (4), 341-369.

Buxton, C. A. (2006). Creating contextually authentic science in a " low-performing" urban elementary school. J. Res. Sci. Teach., 43(7):695-721.

Callahan, R. M. (2005). Tracking and high school English learners: Limiting opportunity to learn. American Educational Research Journal, 42(2), 305.

Carvalho, P. S. and Sampaio, A. (2006). Should we use colours as symbolic representations of hot and cold? Physics Education, 41(3), 263.

Chinn, C. A. and Malhotra, B. A. (2002). Epistemologically authentic inquiry in schools: A theoretical framework for evaluating inquiry tasks. Sci. Ed., 86(2):175-218.

Coble, K. A., Cochran, G., Larrieu, D., Bailey, J., Sanchez, R., Cominsky, L., and McLin, K. (2010). Probing student understanding of cosmology. In American Astronomical Society Meeting Abstracts #215, volume 42 of Bulletin of the American Astronomical Society.

Cole, M. (1988). Cross-cultural research in the sociohistorical tradition. Human development, 31(3), 137-157.

Cole, M. & Wertsch, J.V. (1996). Beyond the Individual-Social Antimony in Discussions of Piaget and Vygotsky. Human Development, 39: 250-256.

Cole, M. and Engeström, Y. (1993) A cultural-historical approach to distributed cognition, in: G. Salomon (Ed.), Distributed cognitions: Psychological and educational considerations (New York, Cambridge University Press), 1-46.

Collins, A., Brown, J.S., and Newman, S. (1989). Cognitive apprenticeship: Teaching the crafts of reading, writing, and mathematics. In L. Resnick (Ed.), Knowing, Learning, and Instruction: Essays in Honor of Robert Glaser. Hillsdale, NJ: Lawrence Erlbaum Associates.

Common Core State Standards Iniative. (2010). Common Core State Standards for English language arts and literacy in historical/social studies, science, and technical subjects. Retrieved from http://www.corestandards.org.

Cosmos: A Personal Voyage. (n.d.). In Wikipedia. Retrieved February 2, 2012, from http://en.wikipedia.org/wiki/Cosmos:_A_Personal_Voyage.

Crain, R. L. (2010). Institutionalization in action: Interactive science center interactivity and materiality from the family perspective. PhD thesis, University of California, Santa Cruz.

Creswell, J. W. (2002). Educational research: Planning, conducting and evaluating, quantitative.

Creswell, J. W. (2003). Research Design: Qualitative, Quantitative, and Mixed Methods Approaches (2nd Edition). Sage Publications, Inc, 2nd edition.

Creswell, J. W., Hanson, W. E., Plano, V. L. C., & Morales, A. (2007). Qualitative research designs selection and implementation. The Counseling Psychologist, 35(2), 236-264.

Cuevas, P., Lee, O., Hart, J., & Deaktor, R. (2005). Improving science inquiry with elementary students of diverse backgrounds. Journal of Research in Science Teaching, 42(3), 337-357.

Darder, A. (1991). Culture and Power in the Classroom: A Critical Foundation for Bicultural Education (Critical Studies in Education & Culture). Bergin & Garvey Paperback.

diSessa, A. (1983). Phenomenology and the Evolution of Intuition, chapter 2. Lawrence Erlbaum Associates.

Dodick, J., & Orion, N. (2003). Cognitive factors affecting student understanding of geologic time. Journal of research in science teaching, 40(4), 415-442.

Duensing, S. (2006). Culture Matters, in Learning in places: the informal education reader. Ed. Zvi Bekerman, Nicholas C. Burbules, Diana Silberman-Keller. Counterpoints, New York, NY.

Engeström, Y. (1987). Learning by expanding: An activity-theoretical approach to developmental research. Helsinki: Orienta-Konsultit.

Engeström, Y. (1999). Innovative learning in work teams: analysing cycles of knowledge creation in practice, in: Y. Engeström et al (Eds.) Perspectives on Activity Theory, (Cambridge, Cambridge University Press), 377-406.

Engeström, Y. (2001). Expansive learning at work: Toward an activity theoretical reconceptualization. Journal of education and work, 14(1), 133-156.

Engeström, Y., & Sannino, A. (2010). Studies of expansive learning: Foundations, findings and future challenges. Educational Research Review.

Engeström, Y., & Sannino, A. (2011). Discursive manifestations of contradictions in organizational change efforts: A methodological framework. Journal of Organizational Change Management, 24(3), 368-387.

Evagorou, M. (2009). An Investigation of the Potential of Interactive Simulations for Developing System Thinking Skills in Elementary School: A case study with fifth-graders and sixth-graders. International Journal of Science Education 31(5), 655-674.

Fox, P. (1932). The Adler planetarium and astronomical museum of Chicago. Popular Astronomy, 40, 125.

Fradd, S. H. and Lee, O. (1999). Teacher's Roles in Promoting Science Inquiry with Students from Diverse Language Backgrounds.

Freire, P. (1993). Pedagogy of the Oppressed. 1970. New York: Continuum.

Freire, P., & Macedo, D. (1987). Literacy: Reading the word and theworld. Westport, CT: Bergin & Garvey.

Friedman, V. (2008). Data visualization and infographics. Graphics, Monday Inspiration, 14, 2008.

Genesee, F., Lindholm-Leary, K., Saunders, W., and Christian, D. (2005). English language learners in U.S. schools: An overview of research findings. Journal of Education for Students Placed at Risk (JESPAR), 10(4):363-385.

Gentner, D. (1989). The mechanisms of analogical learning. In Vosniadou, S., & Ortony, A. (Eds.), *Similarity and analogical reasoning*. Cambridge University Press: 199-241.

Gentner, D., & Markman, A. B. (1997). Structure mapping in analogy and similarity. *American psychologist, 52*(1), 45.

Gibbons, P. (2002). Scaffolding language, scaffolding learning: Teaching second language learners in the mainstream classroom. Portsmouth, NH: Heinemann.

Gipps, C. (1999). Socio-cultural aspects of assessment. Review of Research in Education, 24, 355-392.

Gorski, P. (2008) | Volume 65 | Number 7 Poverty and Learning Pages 32-36 The Myth of the Culture of Poverty

Granott, N. (2005). Scaffolding dynamically toward change: Previous and new perspectives. New Ideas in Psychology, 23(3):140–151.

Griffin, P., & Cole, M. (1984). Current activity for the future: The Zo-ped. New Directions for Child and Adolescent Development, 1984(23), 45-64.

Gutiérrez, K. D. and Rogoff, B. (2003). Cultural ways of learning: Individual traits or repertoires of practice. Educational Researcher, 32(5):19-25.

Gutiérrez, K. D., & Rogoff, B. (2003). Cultural Ways of Learning : Individual Traits or Repertoires of Practice Cultural Styles : A Way of Talking About. Educational Researcher, 32(5), 19-25.

Hegarty, M., Kriz, S., & Cate, C. (2003). The roles of mental animations and external animations in understanding mechanical systems. Cognition and instruction, 21(4), 209-249.

Hesse, M. B. (1966). Models and analogies in science (Vol. 7). Notre Dame: University of Notre Dame Press.

High Performance AstroComputing Center (HiPACC) website. (2014). Retrieved from hipacc.ucsc.edu on February 14, 2014.

Hogan, K., & Fisherkeller, J. (1996). Representing students' thinking about nutrient cycling in ecosystems: Bidimensional coding of a complex topic. Journal of Research in Science Teaching, 33(9), 941-970.

Hohenstein, J., & Ash, D. (in review). A window on the relational shift: Families' use of analogy and comparison as a tool for learning in a science museum, Research in Science Education.

Hooper-Greenhill, E. (2004). Measuring learning outcomes in museums, archives and libraries: The learning impact research project (LIRP). *International Journal of Heritage Studies*, *10*(2), 151-174.

John-Steiner, V. and Mahn, H. (1996). Sociocultural approaches to learning and development: A Vygotskian framework. Educational Psychologist, 31(3/4).

Johnson, R. B., & Onwuegbuzie, A. J. (2004). Mixed methods research: A research paradigm whose time has come. Educational researcher, 33(7), 14-26.

Kaptelinin, V. (1996). Activity theory: implications for human-computer interaction. Context and consciousness: Activity theory and human-computer interaction, 103-116.

Kiboss, J. K., Ndirangu, M., and Wekesa, E. W. (2004). Effectiveness of a Computer-Mediated simulations program in school biology on pupils' learning outcomes in cell theory. Journal of Science Education and Technology, 13(2).

Kiboss, J. K., Ndirangu, M., and Wekesa, E. W., 2004. Effectiveness of a Computer-Mediated simulations program in school biology on pupils' learning outcomes in cell theory. Journal of Science Education and Technology, 13(2).

Kluger-Bell, B. (2000). Recognizing inquiry: Comparing three hands-on teaching techniques. Foundations (Vol. 2, NSF Rep. No. NSF99148, pp. 39–50).Washington, DC: National Science Foundation.

Kohli, R. (2009). 'Critical race reflections: valuing the experiences of teachers of color in teacher education', Race Ethnicity and Education,12:2,235 — 251.

Kohn, A. (2000). The Case Against Standardized Testing: Raising the Scores, Ruining the Schools. Heinemann.

Kozol, J. (1988). Savage inequalities: Children in America's schools. New York: Harper-Collins.

Kramer, M. (2013, November 4). “Dark Universe” Planetarium Show Reveals Hidden Cosmos. *SPACE.com*. Retrieved from space.com.

Krathwohl, D. R., Bloom, B. S., & Masia, B. B. (1964). Handbook II: Affective Domain. New York: David McKay.

Ladson-Billings, G. (2006). From the achievement gap to the education debt: Understanding achievement in US schools. Educational researcher, 35(7), 3-12.

Latour, B. & Woolgar, S. (1979). Laboratory Life: The Construction of Scientific Facts. Princeton University Press.

Lave, J., & Wenger, E. (1991) Situated learning. New York: Cambridge University Press.

Lee, H. S., Liu, O. L., Pallant, A., Roohr, K. C., Pryputniewicz, S., & Buck, Z. E. (2014). Assessment of uncertainty‐infused scientific argumentation. Journal of Research in Science Teaching, 51(5), 581-605.

Lee, O. (1999). Equity Implications Based on the Conceptions of Science Achievement in Major Reform Documents. Review of Educational Research, 69(1), 83.

Lee, O. & Fradd, S. H. (1998). Science for All, including Students from Non-English-Language Backgrounds. Educational Researcher, 27(4).

Lee, O., Maerten-Rivera, J., Penfield, R. D., LeRoy, K. and Secada, W. G. (2008), Science achievement of english language learners in urban elementary schools: Results of a first-year professional development intervention. J. Res. Sci. Teach., 45: 31–52.

Lemke, J. L. (1990). Talking Science: Language, Learning and Values. Language and Educational Processes. Ablex Publishing, Westport, Connecticut.

Lemke, J. L. (2001). Articulating communities: Sociocultural perspectives on science education. Journal of Research in Science Teaching, 38(3), 296-316.

Lemke, J. (2011). The secret identity of science education: masculine and politically conservative?. Cultural Studies of Science Education, 6(2), 287-292.

Leont'ev, A. N. (1974). The problem of activity in psychology. *Journal of Russian and East European Psychology*, *13*(2), 4-33.

Limón, M. (2001). On the cognitive conflict as an instructional strategy for conceptual change: a critical appraisal. Learning and Instruction, 11(4-5): 357-380.

Lincoln, Y. S., & Guba, E. G. (2001). Naturalistic inquiry. 1985. VALLES, M. Técnicas.

MacDonald, Sharon (2002). Behind the Scenes at the Science Museum. Oxford, UK: Berg.

Mai, T. & Ash, D. (2013). Reclaiming Scaffolding: Meaning-Making and Diverse Learners in an Urban Science Museum. In D. Ash, J. Rahm and L. Melber (Eds.), Research to Practice: Theoretically Informed Methodologies for Doing Research in Informal Learning Settings. Sense Publishers. Rotterdam, the Netherlands.

Mascolo, M. (2005). Change processes in development: The concept of coactive scaffolding. New Ideas in Psychology, 23(3):185–196.

Moschkovich, J. N. (2002). A situated and sociocultural perspective on bilingual mathematics learners. Mathematical Thinking and Learning, 4(2&3), 189-212.

Moschkovich, J. N. (2006). Using video to document mathematical activity among bilingual/multilingual learners. Multilingual Mathematics Classrooms Group. International Psychology of Mathematics Education Meeting in Prague, July 2006.

Moschkovich, J. N. (2007). Beyond words to mathematical content: Assessing English learners in the mathematics classroom. In A. H. Schoenfeld (Ed.) Assessing mathematical proficiency (Chapter 20, pp. 345-352). New York: Cambridge University Press.

Moschkovich, J. N. (2008). "I went by twos, he went by one:" Multiple interpretations of inscriptions as resources for mathematical discussions. The Journal of the Learning Sciences, 17(4), 551-587.

Moschkovich, J. (2011). Supporting mathematical reasoning and sense making for English learners. Focus in high school mathematics: Fostering reasoning and sense making for all students. Reston, VA: National Council of Teachers of Mathematics, Inc.

Moschkovich, J. (2013). Principles and Guidelines for Equitable Mathematics Teaching Practices and Materials for English Language Learners. Journal of Urban Mathematics Education, 6(1).

Mosqueda, E. (2010). Compounding inequalities: English proficiency and tracking and their relation to mathematics performance among Latina/o secondary school youth. Journal of Urban Mathematics Education, 3(1) pp.57-81.

Mosqueda, E. (2011). Teacher quality, academic tracking and the mathematics performance of Latino English learners. Latinos/as and mathematics education: Research on learning and teaching in classrooms and communities, 315-340.

Mosqueda, E., Lyon, E. R., Buck, Z. E., & Maldonado, S. I. (in press). Estimating the Influence of Course-Taking Patterns and English Language Proficiency on Science Achievement. Journal of Research in Science Teaching.

Nardi, B. (Ed.), (1996). Context and consciousness: Activity theory and human-computer interaction. Cambridge, MA: MIT Press.

National Center for Education Statistics (NCES). (2011). The condition of education 2010. Indicator 5: Language minority school-age children. Washington, DC: U.S. Department of Education. Retrieved March 25, 2011, from http://nces.ed.gov/programs/coe/2010/section1/indicator05.asp.

National Science Foundation. (1996). Review of instructional materials for middle school science. Washington, DC: National Science Foundation.

National Research Council (Ed.). (1996). National science education standards. National Academy Press.

National Research Council. (2011). A framework for K-12 science education: Practices, crosscutting concepts, and core ideas. Washington, DC: National Academies Press.

National Science Board (2006). Science and Engineering Indicators 2006. Two volumes. Arlington, VA: National Science Foundation (volume 1, NSB 06-01; volume 2, NSB 06-01A).

NGSS Lead States. (2013). Next Generation Science Standards: For States, By States. Washington, DC: The National Academies Press.

Nussbaum, J. (1979). Children's conceptions of the earth as a cosmic body: A cross age study. Science education, 63(1), 83-93.

Nussbaum, J., & Novak, J. D. (1976). An assessment of children's concepts of the earth utilizing structured interviews. Science Education, 60(4), 535-550.

Oakes, J., Ormseth, T., Bell, R., & Camp, P. (1990). Multiplying Inequalities: The effects of race, social class, and tracking on opportunities to learn mathematics and science. Technical report.

Oakes, J. (2005). Keeping track: How schools structure inequality. Yale University Press.

Obama, B. (2014). Remarks by the President in State of the Union Address. January, 2014.

Ogawa, R. T., Loomis, M. and Crain, R. (2009), Institutional history of an interactive science center: The founding and development of the Exploratorium. Sci. Ed., 93: 269–292.

Overbye, D. (2013, October 31). What You Can't See is Even Cooler: "Dark Universe" at the Hayden Planetarium. *New York Times*. Retrieved from www.nytimes.com.

Palen, S., & Proctor, A. (2006). Astronomy in the K–8 Core Curriculum: A Survey of State Requirements Nationwide. Astronomy Education Review, 5(1), 23-35.

Palincsar, A. S. and Brown, A. L. (1986). Interactive teaching to promote independent learning from text. The Reading Teacher, 39(8):771-777.

Palmer, D. (2001). Students' alternative conceptions and scientifically acceptable conceptions about gravity. International Journal of Science Education, 23(7), 691-706.

Panagiotaki, G., Nobes, G., & Potton, A. (2009). Mental models and other misconceptions in children's understanding of the earth. Journal of Experimental Child Psychology, 104(1), 52-67.

Pea, R. D. (2004). Commentary: The social and technological dimensions of scaffolding and related theoretical concepts for learning, education, and human activity. Journal of the Learning Sciences, 13(3):423–451.

Pease-Alvarez, L. and Hakuta, K. (1992). Enriching Our Views of Bilingualism and Bilingual Education. Educational Researcher, 21(2):4-19.

Peña, B. M., & Gil Quilez, M. J. (2001). The importance of images in astronomy education. *International Journal of Science Education*, *23*(11), 1125-1135.

Piaget, J., and Inhelder, B. (1969). The Psychology of the Child. New York: Basic Books.

Plummer, J. (2009). Early Elementary Student's Development of Astronomy Concepts in the Planetarium. Journal of Research in Science Teaching, 46(2), 192-209.

Prather, E. E., Slater, T. F., & Offerdahl, E. G. (2002). Hints of a fundamental misconception in cosmology. Astronomy Education Review, 1(2), 28-34.

Primack, J. R. and Abrams, N. E. (2006). "The View from the Center of the Universe: Discovering Our Extraordinary Place in the Cosmos," New York: Riverhead Books.

Rahm, J. (2012). Activity Theory as a Lens to Examine Project-Based Museum Partnerships in Robotics. In Understanding Interactions at Science Centers and Museums (pp. 147-171). SensePublishers.

Raphling, B. and Keane-Timberlake, S. (1997). How Down to Earth is the Universe?. Visitor Behavior, 12(1), 17-20.

Reynoso, H., Enrique Fierro, H., Gerrdo Torres, O., Vicentini-Missoni, M., & Josefina Pérez de Celis, H. (1993). The alternative frameworks presented by Mexican students and teachers concerning the free fall of bodies. International journal of science education, 15(2), 127-138.

Richardson, T. and Villenas, S. (2000). "Other" encounters: Dances with whiteness in multicultural education. Educational Theory, 50(2):255-273.

Rodriguez, G. (2004). Towards a New Mainstream? [Video Webcast]. Published by the Center for the Future of Museums. Retrieved from http://futureofmuseums.org.

Rosebery, A.S., Warren, B., Conant, F. R. (1992). Appropriating Scientific Discourse: Findings From Language Minority Classrooms. Journal of the Learning Sciences. 2(1).

Ruggiero, S., Cartelli, A., Dupre, F., & Vicentini-Missoni, M. (1985). Weight, gravity and air pressure: Mental representations by Italian middle school pupils. The European Journal of Science Education, 7(2), 181-194.

Sadler, P. M. (1992). The Initial Knowledge State of High School Astronomy Students. PhD thesis, Harvard University, Cambridge, MA.

Schoemer, J. (1999). The voyage study: A Front-End evaluation for a scale model of the solar system. Master's thesis, University of Colorado.

Schneps, M. H., and P. M. Sadler. 1988. A private universe. Pyramid Films, Santa Monica, CA.

Shaw, J. M. (1997). Threats to the validity of science performance assessments for English language learners. J. Res. Sci. Teach., 34: 721–743.

Shaw, J. M., Bunch, G. C., & Geaney, E. R. (2010). Analyzing language demands facing English Learners on science performance assessments: Development and use of the SALD framework. Journal of Research in Science Teaching, 47(8)

Sherin, B., Reiser, B.J., and Edelson, D. (2004). Scaffolding Analysis: Extending the Scaffolding Metaphor to Learning Artifacts. Journal of the Learning Sciences, 13(3), 387–421

Skinner, B. F. (1953). Science and human behavior. Simon and Schuster.

Small, K. J. and Plummer, J. D. (2010). Survey of the goals and beliefs of planetarium professionals regarding program design. Astronomy Education Review, 9(1).

Smith, R. G., & Peacock, G. (1992). Tackling contradictions in teachers' understanding of gravity and air resistance. Evaluation & Research in Education, 6(2-3), 113-127.

Smith III, J. P., diSessa, A. A., & Roschelle, J. (1994). Misconceptions reconceived: A constructivist analysis of knowledge in transition. The journal of the learning sciences, 3(2), 115-163.

Sneider, C. I., & Ohadi, M. M. (1998). Unraveling students' misconceptions about the earth's shape and gravity. Science Education, 82(2), 265-284.

Sneider, G., & Pulos, S. (1983). Children's cosmographies: Understanding the earth's shape and gravity. Science Education, 67(2), 205-221.

Solano-Flores, G. (2008). Who is given tests in what language by whom, when, and where? The need for probabilistic views of language learning in the testing of English language learners. Educational Researcher, 37(4), 189-199.

Solano-Flores, G., Nelson-Barber, S. (2001). On the Cultural Validity of Science Assessments. Journal of Research in Science Teaching, 38(5), 553-573.

Stathopoulou, C., & Vosniadou, S. (2007). Conceptual change in physics and physics-related epistemological beliefs: A relationship under scrutiny. Reframing the conceptual change approach in learning and instruction, 145-163.

Steen, L. A. (2001). Mathematics and numeracy: Two literacies, one language. The mathematics educator, 6(1), 10-16.

Sterman, J. D. (2002). All models are wrong: reflections on becoming a systems scientist. System Dynamics Review, 18(4), 501-531.

Stoddart, T., Pinal, A., Latzke, M., & Canaday, D. (2002). Integrating inquiry science and language development for english language learners. Journal of Research in Science Teaching, 39(8), 664-687.

Stoddart, T., Solis, J., Tolbert, S., & Bravo, M. (2010). Effective science teaching for English language learners. In D Sunal & C Sunal. Teaching science with Hispanic ELLs in K-16 classrooms (pp. 151-181). Albany NY: Information Age Publishing.

Strike, K. A. & Posner, G. J. (1985) . A conceptual change view of learning and understanding. In L. H. T. West & A. L. Pines (Eds.), Cognitive structure and conceptual change (pp. 211-231). New York: Academic Press.

Sweetman, D., Badiee, M., & Creswell, J. W. (2010). Use of the Transformative Framework in Mixed Methods Studies. Qualitative Inquiry, 16(6), 441-454.

Tabak, I. (2004). Synergy: A complement to emerging patterns of distributed scaffolding. Journal of the Learning Sciences, 13(3):305–335.

Taber, K. S. (2001). When the analogy breaks down: modelling the atom on the solar system. *Physics Education*, *36*(3), 222.

The Universe (TV series). (n.d.). In Wikipedia. Retrieved February 2, 2012, from http://en.wikipedia.org/wiki/The_Universe_(TV_series).

Tretter, T. R., Jones, M. G., Andre, T., Negishi, A., & Minogue, J. (2006). Conceptual boundaries and distances: Students' and experts' concepts of the scale of scientific phenomena. Journal of research in science teaching, 43(3), 282-319.

Trundle, K. C. , Atwood, R. K. and Christopher, J. E. (2006) Preservice elementary teachers' knowledge of observable moon phases and pattern of change in phases. Journal of Science Teacher Education 17:(2) , pp. 87-101

United States Census Bureau. (2011). Census data for the state of California. Retrieved from http://quickfacts.census.gov/qfd/states/06000.html on July 14, 2012.

Von Secker (2002). Effects of Inquiry-Based Teacher Practices on Science Excellence and Equity.

Vosniadou, S. (Ed.). (2010). International handbook of research on conceptual change. Routledge.

Vosniadou, S. and Brewer, W. F. (1992). Mental models of the earth: A study of conceptual change in childhood. Cognitive Psychology, 24:535-585.

Vygotsky, L. (1978). Mind in Society: The Development of Higher Psychological Processes. Cambridge, MA: Harvard University Press.

Warren, B., Ballenger, C., Ogonowski, M., Rosebery, A. S., and Hudicourt-Barnes, J. (2001). Rethinking diversity in learning science: The logic of everyday sense-making. J. Res. Sci. Teach., 38(5):529-552.

Warren, B., Pothier, S., and Ogonowski, M. (2005). "Everyday" and "Scientific": Rethinking Dichotomies in Modes of Thinking in Science Learning, pages 119+. Lawrence Erlbaum Associates, Mahwah, NJ.

Weil, S. (1999). Transformed from a cemetery of bric-a-brac. In *Perspectives on Outcome Based Evaluation for Libraries and Museums*. Washington, D.C.: Institute of Museum and Library Services.

Weinberg, S. (1993). The first three minutes: a modern view of the origin of the universe. Basic Books.

Wells, G. (1981). 'Language as interaction.' Learning through interaction. Cambridge: Cambridge UniversityPress.

Wells, G. (1996). Using the tool-kit of discourse in the activity of learning and teaching. *Mind, Culture, and Activity, 3*(2): 74-101.

Wells, G. (1999). Dialogic inquiry: Towards a socio-cultural practice and theory of education. Cambridge University Press.

Wells, G. (2002). The role of dialogue in activity theory. *Mind, Culture, and Activity*, *9*(1):43-66.

Wells, G. and Claxton, G. (2008) Introduction: Sociocultural Perspectives on the Future of Education, in Learning for Life in the 21st Century: Sociocultural Perspectives on the Future of Education (eds G. Wells and G. Claxton), Blackwell Publishing Ltd, Oxford, UK.

Wertsch, J. V. (1991). Voices of the mind : a sociocultural approach to mediated action. Cambridge, MA: Harvard University Press.

Wertsch, J. V. (1998). Mediated Action in Social Space. Oxford University Press, New York, NY.

Wertsch, J. V. (Ed.) (1981). The concept of activity in soviet psychology. Armonk, NY: M. E. Sharpe.

Wertsch, J.V. (1994) The primacy of mediated action in sociocultural studies. Mind, Culture, and Activity, 1 (4): 202-207.

Wood, D., Bruner, J. S., and Ross, G. (1976). The role of tutoring in problem solving. Journal of Child Psychology and Psychiatry, 17(2):89–100.

Wu, H.-K., Krajcik, J. S., and Soloway, E. (2001). Promoting conceptual understanding of chemical representations: Students' use of a visualization tool in the classroom. Journal of Research in Science Teaching, 38(7):821-842.

Yair, Y., Mintz, R., and Litvak, S. (2001). 3D-virtual reality in science education: An implication for astronomy teaching. Journal of Educational Multimedia and Hypermedia 20: 293–305.

Yin, R. K. (2009). Case study research: Design and methods (Vol. 5). Sage.

Zimmerman, B. J., & Blom, D. E. (1983). Toward an empirical test of the role of cognitive conflict in learning. Developmental Review, 3(1), 18-38.