2008

ASTRAL PROJECTION: THEORIES OF METAPHOR, PHILOSOPHIES OF SCIENCE, AND THE ART O F SCIENTIFIC VISUALIZATION

COX, DONNA J .

http://hdl.handle.net/10026.1/1634

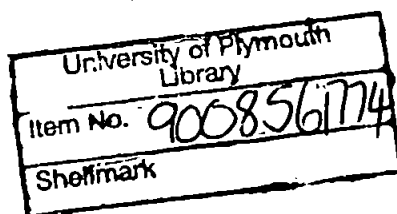# ASTRAL PROJECTION: THEORIES OF METAPHOR, PHILOSOPHIES OF SCIENCE, AND THE ART OF SCIENTIFIC VISUALIZATION

by

DONNA J. COX, M.F.A.

A thesis submitted to the University of Plymouth
In partial fulfillment for the degree of

DOCTOR OF PHILOSOPHY

Planetary Collegium
Advisor: Professor Roy Ascott

December 2008

Donna J. Cox, M.F.A.

Astral Projection:
Theories of Metaphor, Philosophies of Science,
and the Art of Scientific Visualization

This thesis provides an intellectual context for my work in computational scientific visualization for large-scale public outreach in venues such as digital-dome planetarium shows and high-definition public television documentaries. In my associated practicum, a DVD that provides video excerpts, I focus especially on work I have created with my Advanced Visualization Laboratory team at the National Center for Supercomputing Applications (Champaign, Illinois) from 2002-2007.

I make three main contributions to knowledge within the field of computational scientific visualization. Firstly, I share the unique process I have pioneered for collaboratively producing and exhibiting this data-driven art when aimed at popular science education. The message of the art complements its means of production: Renaissance Team collaborations enact a cooperative paradigm of evolutionary sympathetic adaptation and co-creation.

Secondly, I open up a positive, new space within computational scientific visualization's practice for artistic expression--especially in providing a theory of digi-epistemology that accounts for how this is possible given the limitations imposed by the demands of mapping numerical data and the computational models derived from them onto visual forms. I am concerned not only with liberating artists to enrich audience's aesthetic experiences of scientific visualization, to contribute their own vision, but also with conceiving of audiences as co-creators of the aesthetic significance of the work, to re-envision and re-circulate what they encounter there. Even more commonly than in the age of traditional media, on-line social computing and digital tools have empowered the public to capture and repurpose visual metaphors, circulating them within new contexts and telling new stories with them.

Thirdly, I demonstrate the creative power of visaphors (see footnote, p. 1) to provide novel embodied experiences through my practicum as well as my thesis discussion. Specifically, I describe how the visaphors my Renaissance Teams and I create enrich the Environmentalist Story of Science, essentially promoting a counter-narrative to the Enlightenment Story of Science through articulating how humanity participates in an evolving universal consciousness through our embodied interaction and cooperative interdependence within nested, self-producing (autopoetic) systems, from the micro- to the macroscopic. This contemporary account of the natural world, its inter-related systems, and their dynamics may be understood as expressing a creative and generative energy--a kind of consciousness--that transcends the human yet also encompasses it.

Table of Contents

List of Illustrations

Acknowledgements

Author's Declaration

At no time during the registration for the degree of Doctor of Philosophy has the author been registered for any other University award without prior agreement of the Graduate Committee.

All of the materials submitted here are owned by author or the author has permission to submit these materials as part of the thesis.

A program of advanced study was undertaken, which included research, annual monitoring, residency, and thesis in written and practicum form (included here). No coursework was required. To my knowledge, all academic and residency requirements have been satisfied for this PhD program of research.

See Appendix for selected list of Donna Cox publications and presentations of scholarship (or presentations of other forms of creative and performing work) 2000-2007.

Word Count (of main body of thesis): 59,645 words

Signed _Donna C Cox_

Date _11/30/2009_

Preface

In this thesis, I offer an extended account of my unique academic arts and science research practice, in which I collaborate with professionals from a variety of disciplines to create and present animated computational scientific visualizations—what I call visaphors[1]--as part of large-scale outreach projects through high-definition documentary television programming and ultra-high resolution shows for new, high-tech museum venues such as digital domes. In the words of Tom Lucas, a collaborator of many years and principal of Thomas Lucas Productions,[2] my work is focused on "giving millions of people a glimpse of the processes that shape our universe" (Lucas, 2008; see Appendix). I make three claims to contributing new knowledge to the domain of computational scientific visualization through this thesis:

- I share the unique process I have pioneered for collaboratively producing and exhibiting computational scientific visualization for the broader public in mass venues.

- I open up a positive space, for the first time, within scientific visualization's practice of computational science for artistic expression, especially in providing a theory for how this is possible given the limitations imposed by the demands of mapping numerical data and the computational models derived from them onto visual forms.

---

[1] I have coined the term "visaphor" to denote the specialized visual metaphors employed in computational scientific visualization. Visaphors are rendered digitally from supercomputer numerical data. To concrete representations, they map data that are founded upon and derived through compound disciplinary assumptions (such as in the field of mathematics), systems of information, models of science, and approximation methods (Oreskes, Shrader-Frechette, and Belitz, 1994; Shrader-Frechette, 1994; Hesse, 1996; Hallyn, 2000; Lakoff and Nunez, 2000; Nunez, 2000; Reed et al., 2005).

[2] Thomas Lucas Productions: http://www.tlproductions.com/credits.html.

- I demonstrate the creative power of visaphors to provide novel embodied experiences through my practicum as well as my thesis discussion. Specifically, I describe how the visaphors my Renaissance Teams and I create enrich the Environmentalist Story of Science, essentially promoting a counter-narrative to the Enlightenment Story of Science through showing how humanity participates in an evolving universal consciousness through our embodied interaction and cooperative interdependence within nested, self-producing (autopoetic) systems, from the micro- to the macroscopic.

My contributions to new knowledge must be understood within the context of my computational scientific visualization practice.

At its broadest level, visualization makes the "invisible visible." I work within an area of scientific visualization that aims to make visible new understandings of natural phenomena. In our current practice, we visually interpret, represent, and present large-scale computational models of scientific hypotheses. These models are derived from the practice of computational science. Computational science--which has come to be known as the third pillar of scientific inquiry (Reed et al., 2005)[3]--solves large systems of physics equations, generating billions of numbers, within the virtual laboratory of supercomputers. Computational scientists distinguish themselves from computer scientists both through their focus. Computer scientists are concerned with software or hardware innovation, while computational scientists are focused on a science domain to which such technologies might be applied for discovery. Computational scientists' method of inquiry depends upon scientific visualization for its digi-epistemology, a term I have coined that resonates with Ken Golberg's notion of "tele-epistemology," which theorizes the distance between a

---

[3] Theory and experimentation being the first two pillars of scientific inquiry.

viewer and a remote technology through which something is viewed (2001). Scientists develop heuristic models of phenomena based on empirically derived data. Then, together with visualization artists, they work to debug and reveal models from massive, obscuring blocks of geometrically chunked data. From these models, artists develop visualizations-- such as data-informed depictions of supernova explosions or tornado formation (see the Practicum Compilation DVD for examples of visualizations I have developed).

I distinguish this computational science approach from others used in scientific visualization in two ways. Firstly, I have expanded my work beyond that major form in which practitioners--such as those featured in *The Visual Mind: Art and Mathematics* (Emmer, 1993), including myself--create visual representations of algorithms and databases or directly model purely mathematical theorizations. Secondly, I distinguish the focus of my current work from the development of scientific visualization tools used for data discovery and interrogation, which are, as a result, mainly employed in refining models and creating visaphors for audiences within specialized communities. My research group does create interactive visualization tools (see Practicum Compilation DVD for examples of Virtual Director™) to aid in the making of visaphors, but these tools are used to support our process for making visaphors intended for outreach, and so concentrate, again in Tom Lucas's words, on "new heights of drama and aesthetics" (Lucas, 2008; see Appendix).

Currently, my visaphor work is aesthetically designed and directed to the broader public, as a means of popularizing scientific research and contemporary science narratives. Scientific visualization products such as visaphors are generally thought of as a type of scientific communication among ourselves, their creators; our collaborators, the scientists, who provide the computational models; and the popular science educators, who produce infotainments that incorporate a variety of visual methods, including illustrations,

animations, and data-driven visualizations. As a seminal and leading artist in the field of computational scientific visualization, I have created a unique process for producing and exhibiting scientific visualization for the broader pubic in mass venues such as digital planetarium domes and high-definition educational television programs. The process includes special techniques for treating computational data and the coordination of interdisciplinary Renaissance Teams that combine the expertise of artists, scientists, and high-definition feature or museum site educator-writer-producers. I describe this process (see Chapter 2) and its products (see Practicum Overview and Detail) as the first of three major contributions I have made to the field. This contribution is widely acknowledged among my colleagues, as is shown by Paul Fishwick's introduction to my 1988 article "Using the Supercomputer to Visualize Higher Dimensions: An Artist's Contribution to Scientific Visualization," reprinted in honor of *Leonardo*'s 40th anniversary:

> "Donna J. Cox's article [...] is a seminal contribution, not only to *Leonardo*, but to the idea that teams of artists and scientists can and should work closely together in "Renaissance teams" [...] Based on Cox's pioneering work, one is left to speculate how future research can leverage relatively new media...We are left with the conclusion that the best research to push science forward will involve these Renaissance teams." (Fishwick, 2008, p. 390)

The second major contribution I have made to the field of scientific visualization is—for the first time—the opening up of a positive space within its practice for artistic expression, especially in providing a theory for how this is possible given the limitations imposed by the demands of mapping numerical data and the computational models derived from them onto visual forms. I justify this expanded view by arguing--as Brian Harley (2001) has in the case of maps within the study of historical geography--that scientific visualization does not simply hold a mirror to nature and so require only accuracy, clarity, and standardization from us as practitioners. Practitioners within scientific visualization have tended to resist considering themselves artists, preferring to be thought of as

4

communicators instead, but there seems to be some lessening of resistance since the turn of the millennium. Two relatively recent books have attempted to formally establish new regions of the techno-arts through codifying relevant practice in all of its variations and naming the individual artists who have led their development. Stephen Wilson's *Information Arts* (2002) revisits "the relationship of art to scientific and technological research, exploring the pioneering work of artists with emerging research" (p. 5). I am included as a pioneering artist within "Digital Information Systems / Computers" as well as "Algorithms, Mathematics, Fractals, Genetic Art, and Artificial Life," in contrast with such areas as "Biology" approaches; "Telecommunications"; or "Kinetics, Sound Installations, and Robots." Within my current field of concentration, Digital Information Systems / Computers, I am distinguished as an artist working in "Information Visualization," in contrast with others working in "Virtual Reality"; "Motion, Gesture, Touch, Gaze, Manipulation, and Activated Objects"; "Speech Synthesis, Voice Recognition, and 3-D Sound"; and "Artificial Intelligence." Although I share with other informational visualization artists the common goal of making the "invisible visible" by representing data such as the information of the first internet image (Dodge and Kitchin, 2001), my current work differs from theirs in emphasis as well. Within the "Information Visualization" section of "Information Arts," my work differs from those practicing in complementary but distinctive fields, such as "Surveillance," "Databases and Research Processes," and "Information Organizations and Structures." In contrast, my focus is on the visualization of computational science, this emerging, supercomputer-simulation science, with its technical, artistic, and epistemological challenges.

I am always conscious of these differences in working with colleagues in the scientific visualization arts, what we sometimes refer to as "data-viz." My collaborator, Felice Frankel at Harvard, for example, focuses on imaging and message communication.

5

In particular, she addresses visualization issues surrounding photographs, illustrations, and scanning electron microscopes (Wilson, 2002). In contrast, Paul Fishwick's important work explores mathematical modeling and reveals the aesthetics of computer-science algorithms through visualization (2006). Both Frankel and Fishwick produce visualizations intended for specialized research audiences. In contrast, my practice uses scientific computational models that have been developed in conjunction with domain-expert scientists (e.g., astrophysicists, atmospheric scientists) to heuristically research and represent scientific hypotheses and discover new visual forms for presenting their science stories to popular culture: large-scale, general audiences.

I distinguish my work from my fellow practitioners in another way, as well. Paul Fishwick's *Aesthetic Computing* (2006), in contrast to Wilson's *Information Arts*, defines a hybrid field that "is concerned with the impact and effects of aesthetics on the field of computing" (p. 3), in which aesthetics is defined as "sense perception and the associated cognitive state of a person who is under the influence of an aesthetic experience" (p. xiii) and computing is taken to be broadly synonymous with computer science in all of its forms (p. 5). Fishwick distinguishes aesthetic computing from the information arts by their differing goals. Aesthetic computing seeks to "modify computer science through the catalysis of aesthetics" rather than to employ digital methods to create new, communicative forms (information arts) or new artistic expressions or forms of art (computer arts, digital arts media). Although my thesis discussion and practicum draw on information arts principles, it would be accurate to say that they represent an aesthetic computing approach. Fishwick classifies types of aesthetic computing by their *modality*, how they "interface and interact with objects"; their *culture*, how they "manifest" in relation to "specific artists, art movements, and genre:" and *quality*, how they incorporate "general aesthetic qualities" (p. 13). My invited, chapter-length contribution to the volume

6

treats "metaphoric mappings" as a basis for the "art of visualization" and appears in the "Art and Design" section (Cox, 2006, pp. 89-114), rather than in sections devoted to topics such as "Philosophy and Representation," "Mathematics and Computing," and "Interface and Interaction." In the chapter, I discuss how visualization artists use a creative metaphoric mapping process when mediating, filtering, and using data to communicate scientific theories. The process I have developed to do so is represented in the volume because of its importance in contributing to the practice of aesthetic computing, especially in terms of the *modality* of visaphors as embodied metaphors that may be experienced familiarly in terms of *culture*--as modern scientific illustrations or animations in telling science stories--even as they evoke a range of general *aesthetic qualities*, including beauty, wonder, imaginative projection, and a re-envisioning of the perceived real.

The third major contribution I have made through my work is not limited to the field of scientific visualization, but it does provide an example of what we may create within the scope of our funding and project obligations and with the tools and media at our disposal. That is, I have worked through my most recent scientific visualizations to enrich the Environmentalist Story of Science, essentially promoting a counter-narrative to the Enlightenment Story of Science that describes how humanity participates in an evolving universal consciousness through our embodied interaction and cooperative interdependence within nested, self-producing (autopoetic) systems, from the micro- to the macroscopic (Margulis and Sagan, 1986; Maturana and Varela, 1980, 1987; Barlow, 1991; Waldrop, 1992; Kauffman, 1995). I have done so not through directly altering project narratives, in either their scripts or the sweep of their complete visual offerings, but through incorporating and manipulating visaphors: the specialized, data-informed visual metaphors that are themselves aesthetically composed of nested, autopoetic systems. These visaphors enact for audiences a vital, sensory experience that they then incorporate

7

into their embodied selves and manifest in the systems of which they are a part--including

our highly situated and partial reality that is ever subject to vision and revision.

PRACTICUM

The art that is coming will give formal expression to our scientific conviction.

---Franz Marc

(from *Man and his Symbols*, Carl Gustav Jung, 1968, p. 302)

Practicum Overview

My artistic work in computational scientific visualization is aesthetically designed and directed to the broader public as a means of popularizing scientific research and contemporary science narratives. I direct the Advanced Visualization Laboratory team (AVL) at the National Center for Supercomputing Applications (NCSA) in creating cinematic visaphor sequences (superficially similar to animated clips or short films) for large-scale outreach and distribution in popular culture venues. These visaphor sequences serve as digital imagery in ultra-high resolution, immersive digital dome shows and high-definition television documentaries—with audiences that number in the millions.

A cinematic visaphor sequence (what throughout this thesis I refer to simply as a "visaphor") is an animated, computer graphics imaging (CGI), time-based visualization of computational science that I collaborate with a Renaissance Team of scientists, visualization artists, and technicians to generate. Our visaphor development process is unique to computational scientific visualization and the methods I have pioneered for creative production within the field (this process is described in Chapter 2). My Renaissance Team and I also collaborate with science producer-writer-educators to incorporate our visaphors into large-scale outreach projects (i.e., various types of distributed exhibits and shows). The process we use to contextualize our work is similar to those used to incorporate complex, artistic, digital elements in the production of full-length feature films. However, visaphors are not simply digital special effects, such as those presented in Hollywood movies. They incorporate research from peer-reviewed computational science studies and applied computer graphics visualization techniques.

Our visaphors must be incorporated into large-scale projects strategically, so that they complement the documentary's narrative and its visual style, from camera work to color values to subtle renderings of metaphoric development customized for the production. In the body of work presented here, we were aware from the start that the visaphors we created would be incorporated into a larger project. Our visaphor sequences are also sometimes shared with smaller and more specialized public audiences as is, without incorporation into large-scale projects. For example, we exhibit visaphor sequences in art exhibits and conference demonstrations for specialized audiences.

Our cinematic visaphor sequences are most often viewed by the public through their incorporation into ultra-high resolution digital dome shows at museum-based planetariums and IMAX theaters and into high-definition television documentaries created for NOVA and aired on PBS (Public Broadcasting Service) or created for and aired on the Discovery Channel. They are embedded within documentaries in combination with visual elements created by other project contributors (e.g., illustration, live action) and enhanced through yet other contributors' non-visual elements, such as voice-over narration, script, and music or sound effects.

Practicum Package

For the Practicum, I have submitted two DVDs, one a compilation of excerpts from a number of projects and the other a single project from end-to-end, the *Black Holes* digital-dome show promotional DVD. The material on these two DVDs constitutes the practicum submission intended to meet the requirements of my doctoral degree.

(1) Practicum Compilation DVD

1. General Visaphor Sequences

2. Virtual Tools

Excerpts from:

3. *Hunt for the Supertwister: Chasing Nature's Most Powerful Tornadoes* PBS *NOVA* show

4. *Black Holes: The Other Side of Infinity* digital-dome show (round format)

5. *Monster of the Milky Way: A Supermassive Black Hole* PBS *NOVA* show

On the Practicum Compilation DVD, I have placed cinematic visaphor sequences by themselves, to clearly distinguish them from other documentary elements of completed shows, demonstrate important concepts, and illustrate the development of this new art form. Some of the sequences provided under General Visaphor Sequences (such as the Monterey Bay Ocean) have not yet appeared in large-scale projects, but have appeared in smaller art exhibits. I have provided demonstrations, too, of collaborative tools we have developed for creating visaphors with colleagues near and far.

The Practicum Compilation DVD also provides excerpts from three large-scale outreach productions to demonstrate the collaborative contexts within which my visaphors have been embedded. I have organized these excerpts under show scenes (in which visaphors are embedded) and visaphor sequences (isolated from surrounding scenes to clearly distinguish them from other show material).

I want to stress that these visaphor sequences are the final aesthetic results of a process that begins with massive data derived from scientific simulations run on supercomputers. These visaphors require concentrated human effort and creative vision to produce. Many of these visaphor sequences require months of exploration of computational data and iterative aesthetic render tests before final sequences can be realized. For example, in creating the tornado visaphor sequences on this Practicum Compilation DVD--some of which were later used in the large-scale outreach project *Hunt for the Supertwister--* we collaborated with NCSA Senior Research Scientist and University of Illinois Professor of Atmospheric Sciences Bob Wilhelmson and his team,

13

who simulated a 200 mph-wind, massive tornado similar to the one Manchester, South Dakota suffered in Summer 2003 using NCOMMAS (NSSL Collaborative Model for Multiscale Atmospheric Simulation). Starting with sensor data from the recorded pre-storm conditions near Manchester, the science team ran calculations on NCSA's IBM p690 computing cluster to produce a 100 x 100 x 25 km virtual domain of super cell storm and tornado activity, resulting in 650 billion bytes of data. Using a human-intensive, highly iterative process, my team at AVL and I then translated that data into a dynamic, high-definition, animated visualization of the tornado's birth and growth. To render these visaphor sequences, we used a visualization cluster composed of 40 dual-processor 2.4 GHz Intel Xeon nodes, each with 2GB of RAM and about 100 gigabytes of local disk space, plus seven I/O nodes with about 290GB of shared disk space apiece. Without access to such supercomputing resources, our rendering work would have taken 970 days of dual-processor CPU processing (NCSA, 2004). As usual, we produced much more visaphor footage than was actually used in the NOVA show and conducted many digital tests that are also not shown here.

(2) *Black Holes* Digital-Dome Show Promotional DVD

Black Holes: The Other Side of Infinity is a promotional DVD released by Spitz[4] distributor for the digital-dome show, with round dome formatted version, rectangular TV version, and other promotional materials that include interviews with key production personnel. *Black Holes: The Other Side of Infinity* was a Denver Museum of Nature and Science (DMNS) digital dome show narrated by Liam Neeson that previewed in February 2006; it was designed to be experienced "live" within an immersive large-scale

---

[4] Since 1945, ES Spitz, Inc. has been an international leader in digital-dome and opto-mechanical dome manufacturing (http://spitzinc.com/). In its first 18 months of distributing Black Holes, ES Spitz, Inc. licensed the show to more than 30 theaters ranging in size from the nearly 300-seat venue in Chicago's Adler Planetarium down to 50-seat university theaters: http://www.spitzinc.com/fulldome_shows/show_blackholes/index.html].

environment. NCSA's news release describes the show as one that "takes viewers on a thrilling ride to the inside of a supermassive black hole. On the search for black holes across deep space, viewers encounter a range of phenomena visualized by NCSA, including a depiction of the beginning of the universe, the Big Bang, endless seas of dust and gas drawn together by gravity to form the first stars, the collision of two galaxies that cross paths in the vastness of space, and a virtual trip into the center of the Milky Way" (NCSA, 2006). To capture the content and supporting materials of the digital dome show, I have submitted the Spitz, Inc. distributor's promotional DVD, which was created to promote the DMNS digital dome The DVD offers two versions of the show: a dome master version (with a rounded field) and a TV-show format version (with a rectangular field). In addition, the DVD provides extra material, including interviews with primary contributors. I am credited as Co-Producer of the show as a whole and NCSA Producer and Art Director. Currently, fifty-one digital-dome museums have licensed the show (see Appendix: Spitz distribution release, October 2008).

Other Material

In addition to the two DVDs provided in the Practicum package, I refer the readers to two DVDs informally that, like the *Black Holes* digital-dome show promotional DVD, are professionally packaged. I refer to these DVDs to help readers better understand the context of my work, but they <u>do not constitute a submission for meeting degree</u> <u>requirements:</u>

> *Hunt for the Supertwister: Chasing Nature's Most Powerful Tornadoes*: PBS NOVA DVD with the full HD television show, scene selections, and other material.

> *Monster of the Milky Way: A Supermassive Black Hole*: PBS NOVA DVD with the full HD television show, scene selections, and other material

Since excerpts from these feature-length productions are provided on the Practicum Compilation DVD, and I will return to this work frequently throughout my thesis discussion, I next give a description of each show.

Hunt for the Supertwister: Chasing Nature's Most Powerful Tornadoes aired as a high-definition NOVA television episode on PBS in March 2004. NCSA's news release describes the show as focusing "on the search for understanding nature's most violent tornadoes, from daredevil storm chasing in tornado alley to simulating severe weather with the computational resources and visualization expertise of...NCSA." I am credited as Co-Producer of the show as a whole. I also produced and served as art director for NCSA, although the credits do not specifically name these roles. I initiated this project with Tom Lucas and directed the team during production. Full credits are provided by PBS on-line at http://www.pbs.org/wgbh/nova/tornado/credits.html.

Monster of the Milky Way aired as a high-definition NOVA television episode on PBS in October 2006. The Nielson ratings for this show indicate approximately three million viewers (see Lucas Nielson PBS show ratings in Appendix) at its premier. I am credited as Co-Producer for NCSA and as NCSA Producer and Art Director. The DVD is a packaged version of the NOVA episode. A complete script and credit list can be found at http://www.pbs.org/wgbh/nova/blackhole/credits.html.

Black Holes and *Monster of the Milky Way* demonstrate to readers how my team's earlier work is sometimes adapted for later projects, since sequences used in *Black Holes*

16

were reused with revised sequences in *Monster of the Milky Way*. We anticipated doing so

from the start, since the projects were developed together as *The Black Holes Project*,

which was partially funded through a National Science Foundation (NSF) informal science

education grant as well as a grant from NASA. I initiated the project with Tom Lucas of

Thomas Lucas Productions, a firm that specializes in high-end scientific education shows,

and served as co-principal investigator to his principal investigator role. In this case, the

resulting large-scale, creative production outcomes differed in form: *Black Holes* is an

ultra high-resolution digital-dome show (also developed in collaboration with Gates

Planetarium) and *Monster of the Milky Way* is a high-definition, public television show

(also developed in collaboration with PBS). NSF reviewers delighted in the fact that we

proposed this repurposing of computational scientific visualizations in order to be efficient

and consistent, although the two shows' targeted audiences were cut from very different

cultural fabrics.

The DVDs submitted to meet practicum requirements for the thesis demonstrate

some of the forms in which my visaphor work and that of the team I direct reach audiences

in the millions. They also implicitly demonstrate the range of roles in which I have

worked and the variety of resources I have marshaled to realize these collaborative visions

for scientific outreach and education. Of this accomplishment, Tom Lucas writes,

> "I know of no other team anywhere in the world that has worked at such a
> consistently high level to visualize science for public presentation. Part of your
> success, I believe, is that you have built a team of artists and programmers who are
> steeped in science. In addition, you have used your successes to gain a high degree
> of support from your university. Your ability to marshal visualization and
> computational resources at your institution has led to collaborations on a global
> scale." (Lucas, 2008; see Appendix)

A complete list of large-scale outreach projects I have done since 1996 is given in the

Practicum Detail.

Practicum Detail

In its first sections, this document details the contents of the Practicum Compilation DVD, submitted in the Practicum package in partial fulfillment of the requirements for the doctoral degree. The Practicum Compilation DVD includes a set of general visaphor sequences as well as scenes and scene sequences excerpted from three feature-length shows, two of which are <u>not</u> included in the practicum submission in their entirety: *Hunt for the Supertwister: Chasing Natures's Most Powerful Tornadoes* (2004); *Black Holes: The Other Side of Infinity* (2006), which has also been submitted in partial fulfillment of the requirements for the doctoral degree; and *Monster of the Milky Way: A Supermassive Black Hole* (2007). Entries for the scenes and scene sequences included from each show also give details about the show, including my credits and contributions.

In its second section, the document establishes a context for this body of work by giving a history of this most recent stage of my career, in which I have focused on creating supercomputer-supported, cinematic, computational scientific visualizations (what I simply call "visaphors" in the thesis text) for large-scale outreach.

Section I. Advanced Visualization Laboratory Cinematic Computational Visualization Sequences
(selected and arranged on Practicum Compilation DVD as part of the main practicum submission to fulfill requirements for doctoral degree)

A. Practicum DVD General Visaphor Sequences
1: General Visaphor Sequences

1.1 Intellibadge™ Project
1.1.1 Dynamic Bar Chart
1.1.2 Garden Metaphor
1.1.3 Video of SC 02

1.2 Tornado & Ocean
> 1.2.1 TornadoChaser
> 1.2.2 Domefest 2005
> 1.2.3 Monterey Bay

1.3 Star-Galaxy Formation *Black Holes Project*
> 1.3.1 First Star Goes Supernova
> 1.3.2 Galaxy Formation of Milky Way Spiral

1.4 Colliding Galaxies
> 1.4.1 Colliding Galaxies, *Museum of Science & Industry Project*
> 1.4.2 Colliding Galaxies, *The Black Holes Project*

1.5 Milky Way Virtual Flights
> 1.5.1 Virtual Voyage from Milky Way to Virgo, *Runaway Universe*
> 1.5.2 Flight to the Milky Way Galactic Center, *The Black Holes Project*

1.6 Evolution of the Universe
> 1.6.1 Evolution of the Large-Scale Universe, *Runaway Universe*
> 1.6.2 Evolution of the Universe, *The Black Holes Project*

2: Virtual Tools
> 2.1 Virtual Collaboration, BBC excerpt
> 2.2 IGRID-Universe

B. Practicum Compilation DVD Show Excerpts
(ordered from least to most recent)

Project Name:	*Hunt for the Supertwister: Chasing Nature's Most Powerful Tornadoes*
Date Premiered:	first premiered March 1, 2004 repeat showings in 2005, 2006, 2007
Where:	*NOVA* Public Broadcast Corporation (PBS) High Definition (HD) television broadcast Distributed on PBS *NOVA* DVD video
Show Credits:	NCSA Computation and Visualization Co-Producer credits: http://www.pbs.org/wgbh/nova/tornado/credits.html
Show Content:	"*NOVA* profiles the deadliest of tornadoes—supertwisters—and investigates prediction methods. On May 3, 1999, one of the most powerful tornadoes ever recorded carved a path of complete destruction near Oklahoma City. To scientists, the supertwister held sobering lessons about the future for rapidly expanding cities in tornado-threatened areas. Most tornadoes form suddenly and with

little warning. But now meteorologists are on the verge of a breakthrough that may solve the puzzle of how these killer storms spawn and where they are likely to strike. NOVA follows stormchasers as they probe the tornado's deadly secrets. Also included is Lou Wicker of the National Severe Storms Laboratory, who is creating computer models in collaboration with scientists at the National Center for Supercomputing Applications (NCSA)/University of Illinois, that provide exciting insights into the intricate sequence of steps that goes into spawning a twister using a supercomputer model. The visualizations of this supercomputer model were designed and computed at the NCSA by Donna Cox and her Advanced Visualization Laboratory team" (PBS *NOVA* promotional text).

Visaphors appearing in the televised and distributed show:
1. Glyph Tornado visaphors (rendered with various camera moves)
2. Realistic Night-Rendered and Alternate Tornado visaphors
3. Volume-Rendered Tornado visaphors (with various camera moves)
4. Glyph Wind Shear visaphor
5. Doppler Radar-Rendered visaphor
6. Spotlight Vortex-Rendered Tornado visaphor

Practicum Compilation DVD scene excerpts and visaphor sequence log:

3: *Hunt for the Supertwister*
PBS *NOVA* show excerpts
*visaphors embedded within scenes of surrounding material and audio
**visaphor sequences only

(menu1)
*Scene 1 Prologue excerpt (38 sec.)
 **Sequence 1-3: Glyph Tornado visaphor only
 **Sequence 4: Alternate visaphor only

*Scene 3 excerpt (1 min. 52 sec.)
 **Sequence 1: Volume-Rendered Tornado visaphors only
 **Sequence 2: Glyph Tornado visaphors only

*Scene 4 excerpt (1 min. 35 sec.)
 **Sequence 1: Glyph Wind Shear visaphor only
 **Sequence 2: Alternate Night-Render Tornado visaphor only

(menu2)
*Scene 5 excerpt (2 min. 37 sec.)
 **Sequence 1: Volume-Rendered Tornado visaphor only
 **Sequence 2: Glyph Tornado visaphor only
 **Sequence 3: Alternate Doppler Radar-Rendered visaphor only
 **Sequence 4: Spotlight Vortex-Rendered visaphor only

My Contributions:
- Helped initiate project, introducing Tom Lucas and NCSA staff
- Directed Advanced Visualization Laboratory group to create visaphors provided for the show
- Served as NCSA Scientific Visualization Project Director for the show
- Approved visaphor development
- Collaborated directly with Thomas Lucas, the overall show Director, and with computational scientists

Further Project Details:
> http://www.teachersource.com/Books_SoftwareAndVideos/NOVAVide
> os/HuntforSuperTwister_NovaVideo.aspx

Project Name: *Black Holes: The Other Side of Infinity*
= n.b. feature-length promotional DVD also submitted in partial fulfillment of practicum requirement =

Project Format: two recorded show versions on a single DVD: large-scale digital dome version and television format version

the live show, an immersive experience, is not directly recoverable on DVD, but was reproduced in part at the thesis defense in the University of Plymouth's Immersive Vision Theatre, March 2009.

Date Premiered: February 2006

Where: full dome digital planetarium live show (25-minute runtime):
Denver Museum of Nature and Science
Gates Digital Planetarium Dome Show
Denver, Colorado

distributed promotional DVD video (enclosed; contains two, differently formatted versions of same show)

Show Credits: Co-Producer
NCSA Producer and Art Director

Show Content: "There's a place from which nothing escapes, not even light, where time and space literally come to end. It's at this point, inside this fantastic riddle, that black holes exert their sway over the cosmos ... and our imaginations.
In this Museum-produced show, zip through other-worldly wormholes, experience the creation of the Milky Way Galaxy, and

witness the violent death of a star and subsequent birth of a black hole. Mathematical equations, cutting-edge science, and Einstein's theories fill in holes along the way, providing the most complete picture yet on this mysterious phenomenon. Can you feel the pull?" (DMNS promotional text).

Visaphors appearing in the distributed show:

1. Milky Way, alone and with various composites and lens effects
2. First Star Formation and Going Supernova
3. Virtual Voyage from Milky Way to Virgo Cluster of Galaxies
4. Big Bang Expansion
5. Colliding Galaxies I
6. Computed Star Orbits in Milky Way

Practicum Compilation DVD scene excerpts and visaphor sequence log:

4: *Black Holes: The Other Side of Infinity*
digital-dome show excerpts
*visaphors embedded within scenes of surrounding material and audio
**visaphor sequences only

*Prologue
**Sequence 1: Milky Way Galaxy in Galaxies
**Sequence 2: Supernova
*Sequence 3: Milky Way with Earth-Satellite Composite
**Sequence 4: Virtual Voyage from Milky Way to Virgo Cluster
**Sequence 5: Big Bang Expansion
**Sequence 6: First Star Goes Supernova
**Sequence 7: Colliding Galaxies I
**Sequence 8: Star Orbits in Milky Way
Sequence 9: a: **Virtual Voyage through Milky Way
b: * Milky Way with Hamilton Lens Effect
Production End Credits in TV Format

My Contributions:
- Helped initiate project with Tom Lucas
- Served as Co-Principal Investigator on the original National Science Foundation proposal: The Black Holes Project
- Designated NCSA Scientific Visualization Project Director, directing Advanced Visualization Laboratory group
- Closely directed and approved all NCSA visaphor development
- Provided input on script, other scientific visualizations, and illustrations in the show
- Contributed "hands-on" development of various shots, including first star going supernova and evolution of universe
- Provided input on choreography, color, and final approval for all shots for the show

- Collaborated directly with Thomas Lucas, the overall show Director; computational and consulting scientists; and Denver Museum of Nature and Science producers and production staff

Distribution: Spitz, Inc. continues to distribute the show worldwide; it has now appeared at 51 planetariums (see Appendix). (The show's visuals can be adapted to appear in different types of planetarium environments).

Project Name: *Monster of the Milky Way: A Supermassive Black Hole*

Date Premiered: original PBS broadcast date: October 31, 2006
multiple broadcasts since October 2006

Where: NOVA Public Broadcast Corporation (PBS) high definition (HD) television broadcast
distributed on NOVA PBS DVD video (enclosed)

Show Credits: NCSA Producer and Art Director
NCSA Co-Producer
credits: http://www.pbs.org/wgbh/nova/blackhole/credits.html

Show Content: "Astronomers are closing in on the proof they've sought for years that one of the most destructive objects in the universe—a supermassive black hole—lurks at the center of our own galaxy. Could it flare up and consume our entire galactic neighborhood? Join NOVA on a mind-bending investigation into one of the most bizarre corners of cosmological science: black hole research. From event horizon to singularity, the elusive secrets of supermassive black holes are revealed through stunning computer-generated imagery, including an extraordinary simulation of what it might look like to fall into the belly of such an all-devouring beast. Over 12 different scenes of data-driven scientific visualizations showing astrophysical phenomena are included" (PBS NOVA promotional text).

Visaphors appearing in the televised and distributed show:
1. First Star Formation and Going Supernova
2. Large-Scale Evolution of the Universe
3. Formation of the Milky Way Galaxy
4. Colliding Galaxies I and II
5. Astrophysical Jet
6. Flight to the Center of the Milky Way, and various other Milky Way camera treatments
7. Virtual Voyage from Milky Way to Virgo Cluster
8. Big Bang Expansion
9. Active Galactic Nuclei

10. Colliding Galaxies I
11. Computed Star Orbits in Milky Way

Practicum Compilation DVD scene excerpts and visaphor sequence log:

5: *Monster of Milky Way: A Supermassive Black Hole*
PBS *NOVA* show excerpts
*visaphors embedded within scenes of surrounding material and audio
**visaphor sequences only

(menu1)
*Scene 1 Introduction with embedded visaphors (2 min. 38 sec.)
**Sequence 1: Milky Way with Satellite Composite
**Sequence 2: Evolution of the Universe
**Sequence 3: Hamilton Lens Effect in Milky Way Galaxy
**Sequence 4: First Star Goes Supernova
**Sequence 5: Colliding Galaxies

(menu2)
*Scene 2 excerpt (3 min. 46 sec.)
**Sequence 1: Big Bang
**Sequence 2-4: Milky Way Galaxy
**Sequence 5: Milky Way with Hamilton Lens Effect

*Scene 3 excerpt (2 min. 55 sec.)
**Sequence 1: Star Orbits in Milky Way
**Sequence 2: Milky Way with Hamilton Lens Effect

(menu3)
*Scene 4 excerpt (4 min. 0 sec.)
**Sequence 1: Milky Way with Hamilton Lens Effect
**Sequence 2: Galaxies with Black Holes
**Sequence 3: Big Bang
**Sequence 4: First Star Goes Supernova
**Sequence 5: Milky Way Galaxy Formation
**Sequence 6: Colliding Galaxies
**Sequence 7: Astrophysical Jet

(menu4)
*Scene 5 excerpt (5 min. 3 sec.)
**Sequence 1: Milky Way Galaxy
**Sequence 2: Milky Way with Hamilton Lens Effect
**Sequence 3: Astrophysical Jet with Hamilton Lens Effect
**Sequence 4: Astrophysical Jet
**Sequence 5: Colliding Galaxies
**Sequence 6: Milky Way Formation
**Sequence 7: Galaxies with Black Holes
Production End Credits

My Contributions:

- Helped initiate project with Tom Lucas
- Served as Co-Principal Investigator on the original National Science Foundation proposal: The Black Holes Project
- Acted as NCSA Scientific Visualization Project Director, directing Advanced Visualization Laboratory group
- Closely directed and approved all NCSA visaphor development
- Contributed "hands-on" development of various shots, including First Star Going Supernova, Evolution of the Universe, and Milky Way Formation
- Provided input on choreography, color, and final approval for all shots for the show
- Collaborated directly with Thomas Lucas, the overall show Director, computational and consulting scientists

---

Section II. Career History in Large-Scale Outreach Projects
(ordered from least to most recent)

To give readers a sense of how my work in creating and directing visaphors has developed into large-scale, public outreach projects, I list here those which have had this audience appeal as a primary focus. In these productions my NCSA visaphors (i.e., computational scientific visualizations) have been featured as significant creative components.

I initiated doctoral work under Roy Ascott in 2000, but my professional focus in this area began in 1996 with *Cosmic Voyage*. In the projects listed below, I have served as director/art director and producer/co-producer of the NCSA visaphors and, in some cases, also of the production as a whole. I define these roles in Chapter 2.

- *Cosmic Voyage*, IMAX Film, 1996, Smithsonian Air and Space Museum, Washington, DC Co-Producer of Scientific Visualization and Director of Pixar Sequence

- *Runaway Universe*, NOVA television show2000, Producer and Art Director of NCSA 3D Cosmic Visualizations; NSF funded project "Mapping the Universe".

- *Passport to the Universe*, Digital Dome Show, premiered January 2000, Hayden Planetarium, American Museum of Natural History, New York City, Director of NCSA Computational Visualizations

- *Unfolding Universe*, Discovery Channel high-definition television show, 2002, Director of NCSA visualizations, Producer of show as whole and Art Director of NCSA 3D Cosmic Visualizations

- *Search for Life: Are We Alone?*, American Museum of Natural History, New York City, Digital Dome Show, premiered June 2002, American Museum of Natural History, New York City, Director of NCSA Visualizations

- *IntelliBadge*™, IEEE Supercomputing, November 2002, Baltimore, Maryland, Director of entire project and team responsible for project

- *Hunt for the Supertwister: Chasing Nature's Most Powerful Tornadoes*, NOVA high-definition television show, March 2004, NCSA Computation and Visualization Co-Producer

- *Black Holes: The Other Side of Infinity*, Dome Show, , premiered January 2006, Denver Museum of Nature and Science, Co-PI on original Black Holes Project NSF grant, Co-Producer of project as whole, and NCSA Producer and Art Director

- *Monster of the Milky Way: A Supermassive Black Hole*, NOVA high-definition television show, February 2006, Co-PI on the original Black Holes Project NSF grant, NCSA Producer and Art Director, and NCSA Co-Producer

- *The Fragile Planet*, Dome Show, premiered September 2008, Morrison Planetarium, California Academy of Science, San Francisco, credited for creation of NCSA Milky Way and extragalactic sequences.

- *Monster Black Hole*, National Geographic high-definition television show, premiered December 7 2008, NCSA producer

- *IBEX: Search for the Edge of the Solar System*, Dome Show, December 2008, Adler Planetarium, Chicago, Illinois, NCSA Director Advanced Visualization Lab, Milky Way sequence

THESIS

What is truth? A mobile army of metaphors [...]

-- Friedrich Nietzsche

("On Truth and Lie in an Extra-Moral Sense," 1873;
trans. Walter Kaufmann)

Astral Projection: Theories of Metaphor, Philosophies of Science, and the Art of Scientific Visualization[1]

Introduction

In its broadest sense, visualization involves the process of "making the invisible visible"--a phrase that scientific visualization artists have taken as their unofficial motto. It appears frequently in the pages of the field's flagship publication, *Leonardo: The Journal of the International Society for the Arts, Sciences, and Technology* (Wilson, 2002; Bermudez et al., 2005; Fishwick, 2006; Malina, 2006). Visualization has been an important human activity for tens of thousands of years. From cave paintings to virtual CAVE™ environments (Cruz-Neira, Sandin, and DeFanti, 1993), the process of making the cognitive imagination visually tangible using culturally-dominant technologies is one of the most consistent behaviors of humankind. Culturally-dominant technologies have ranged from primitive carving tools in Paleolithic times to sophisticated digital computers in our own. The power of visualization can be demonstrated in diverse areas such as religion, government, and commerce, as well as science and popular culture.

As a research artist-scientist at the National Center for Supercomputing Applications (NCSA), I have a long history of researching and advancing the field of scientific visualization. Since 1985, when research-based supercomputing was just beginning, I have organized "Renaissance Teams" to collaborate with scientists and technologists in the creation of visualizations for scientific discovery as well as mass

---

[1] In some mystical traditions, astral projection is a form of spirit walk, or "out-of-body" experience, in which the astral body, or semblance of soul, is supposed to leave the body to travel amidst esoteric regions, connected only by a "silver cord." I evoke this experience figuratively here, to suggest the digi-epistemological relationship between the visaphoric manifestation of science stories and the artists' and audiences' embodied experiences of them.

public venues (Cox, 1988a, 1988b, 1989, 1990, 1991, 1996, 1998, 2000a, 2000b). This expertise enables me to formulate this thesis from a unique professional perspective. I do not lightly use the label "unique" with regard to my work or my larger contributions to the field of scientific visualization. To establish the basis for this claim, I begin by explaining the precise nature of the field in which I work.

I work within an area of scientific visualization in which we visually interpret, represent, and present large-scale computational models of scientific hypotheses. My latest contributions focus on visualizing large-scale, scientific computational models that are derived from computational science. Computational science, which has come to be known as the "third pillar of scientific inquiry" (Reed et al., 2005), solves large systems of physics equations within the virtual laboratory of supercomputers. The objective of this new scientific methodology is to describe and predict natural phenomena (Wilhelmson, 1988; Kaufmann, III and Smarr, 1993; Bartz, 1998; Reed et al., 2005). This method of inquiry depends upon scientific visualization to debug, reveal (from massive, obscuring blocks of geometrically chunked data), and heuristically develop the models that result from this processing. The heuristic representations of these models are visaphors, a specialized, high-tech form of visual metaphor.

The visaphors I develop to tell the science stories of these models are designed to capture the imagination and interest of the broader public–in part to provide a means of popularizing cutting-edge scientific research. By the broader public, I mean that we are attempting ultimately to reach not hundreds or thousands, but millions of viewers. Our digital-dome show *Black Holes: The Other Side of Infinity* has been seen by more than 1.4 million people who attended at over fifty planetariums (see Appendix). A letter from Mike Bruno (who works for the show's distributor, Spitz) anticipates a much larger circulation over the lifetime of the show (Bruno, 2008; see Appendix). By all dome-show distribution

32

standards, *Black Holes* is a blockbuster. According to Neilson ratings, the *NOVA* show later developed from this digital-dome show, Monster *of the Milky Way*, had three-million viewers on the night of its first broadcast alone Halloween, 2006. (PUBTV ONLINE, 2006; see Appendix).

Currently, I lead strategic directions for the Advanced Visualization Laboratory (AVL), which I founded. AVL's mission is to work closely with scientists and science communities to create scientific visualization methods and techniques, develop and use interactive visualization applications for data analysis, design and implement visualizations, and work directly with remote collaborators using high-speed networks and advanced visualization systems. Our scientific visualizations aesthetically present science for informal, educational, and public outreach via museum venues (such as digital-dome planetariums), documentary broadcast television, and other public forums.[2] As scientific outreach, their purpose is to inspire as well as to inform.

For the past fourteen years, I have also directed outreach visualization efforts at NCSA, directing scientific visualizations that are data-driven, aesthetically designed, and cinematically presented. A representative selection of these visualizations serves as the practicum portion of this thesis. With the exception of the last visualization listed (Monterey Bay), which stands alone, they have been featured as important creative components that are embedded within collaborative productions (the most recent and significant of my career):

- *IntelliBadge*™, IEEE Supercomputing, 2002 (live event)

---

[2] AVL's mission statement appears on its website: http://avl.ncsa.uiuc.edu.

- *Hunt for the Supertwister*, NOVA, 2004 (television feature) – with

   additional twister visualizations not included and later versions created for

   research

The Black Holes Project

- *Black Holes: The Other Side of Infinity*, Gates Planetarium (Denver), 2006

   (dome show)

- *Monster of the Milky Way*, NOVA, 2006 (television feature) – note:

   includes visaphor sequences from the *Black Holes: The Other Side of*

   Infinity dome show, plus new work produced for this television feature

- *Monterey Bay Ocean Flow*, NSF Grant, 2004 (Orcutt and Smarr, 2008, Cox

   subaward)

As a pioneer in the field, I have created a unique process for producing and

exhibiting scientific visualization for the broader pubic in mass venues. To this process,

forming and leading interdisciplinary Renaissance Teams is especially crucial. I have

found that to bring such complex, collaborative visions to life, my creative practice as an

artist must be complemented by my work as a producer, director, and researcher. In the

Black Holes: The Other Side of Infinity planetarium show, for example, I brainstormed

with external collaborators, helped write the grant proposal for funding, provided input on

the script, and critiqued most of the scenes (not just those visualized). My team and I

visited the Denver Museum of Nature and Science (DMNS) Gates Planetarium and

participated in scientific, educational, and evaluative reviews of the show while it was in

progress. With DMNS, I developed a university contract, dealing with issues of copyright,

royalties, and intellectual property. As producer, I was involved in all of the day-to-day

administrative, financial, and project management aspects of AVL's contributions to the

production. Not only have I produced and directed scientific visualizations for productions, but I have also served as art director of individual scenes because of my responsibility for their aesthetic treatment. When directing the art of scenes, I participate in their creation, production design, color, and cinematic treatment. In many projects, I also provide hands-on, digital color control and camera control of scenes (see Practicum Detail).

My primary goal in theorizing and describing my practice in this thesis is to open up a positive space within computational scientific visualization for artistic expression, especially in providing a theory for how this is possible given the limitations imposed by the demands of mapping numerical data and computational models derived from them onto visual forms. When we contextualize the production and reception of visaphors within the arts, we gain a sense of their cultural origins and impact. The aesthetic forms of visaphors circulate within larger cultural narratives, translated and transformed through the active participation of our audiences in their understanding, reuse, and re-embodiment (they are incorporated into viewers' sense-memories). Visaphors return to us changed and re-energized, grown vast and diverse through having traveled the circuits of our cultural networks, like the ancient tales once carried from many homes to many abroads along the old Silk Road.

The grand narrative scientific visualizations are most apparently used to help tell is the Story of Science, a secular, modern mythology (Swimme and Berry, 1992; Bierlen, 1994). Since the mid-seventeenth century, the European Enlightenment Story of Science has celebrated scientific heroism, especially its objectivity and rationalism, its progress in improving human reason and conquering the unknown. The story has been critiqued in our time as reductionist. However, a newer version that reflects contemporary environmentalist values now seeks to promote increased value for and sensitivity to the

35

natural world and an awareness of our potential for choosing positive outcomes for the biosphere as a whole. This version of the grand narrative revises our understanding of evolutionary science, of emergence in the universe. Rather than evolution's culminating in a human pinnacle, evolution incorporates humanity as an emergent system within the autopoetic layers of the universe (Margulis and Sagan, 1986; Maturana and Varela, 1980, 1987; Barlow, 1991; Waldrop, 1992; Kauffman, 1995). This new story of the universe establishes both our fragile place in the dynamic order of things and our expanded awareness of the universe as greater than the sum of our collective imagination. Rather than dominating nature, humanity comes to play a role in "enabling the Earth and the universe entire to reflect on and to celebrate themselves, and the deep mysteries they bear within them, in a special mode of conscious self awareness" (Swimme and Berry, 1992, p. 1). This new worldview is one of many possible worldviews, but it gains much power from the perceived agency scientific inquiry lends to us and from the self-conscious awareness of our world-making through the metaphoric maps of computational science. We once created a multitude of vital cosmic realities through mythic stories, tales in which we figured-- whether we knew it or not--as creators as well as creation. Today, we are reinventing the sacred through participating once again in creating a new cosmological view of the universe, one enabled through the mythology of science (Kauffman, 2008).

The Western Environmentalist Story of Science is no more told in a single, unified account than the traditional Enlightenment version, but taken across multiple instances its principal, repeated elements form a modern mythology. A unifying theme of this mythology that I embrace is a re-evaluation of the nature of the human and our relationship to the natural, especially at the systemic level, as we consider what it means to be a small part of the universe in its complexity and immensity and how the systems of which we are made up and in which we participate foster cooperative interdependence. When we

36

become aware of computational scientific visualization as an art, and when we popularize that art, we open up a hermeneutic circle between the distributed, institutionalized powers in our culture that authorize, fund, and proscribe key forms of knowledge and the publics that have some degree of agency for reevaluating, resisting, repurposing, and revising them. In coming to accept our field as an art and our role within it as artists, we too stand to gain a self-conscious place within this hermeneutic circle, and the potential to alter our praxis, even if subtly, such as by a shift in emphasis. An awareness of ourselves as artists who are culturally constructing a new view of the universe creatively and ethically compels us to become self-conscious of the stories our work is used to tell and, in turn, the stories we tell through our work.

The scientific community and the scientific visualization experts who identify with it have resisted reading the cultural significance of the images we create. As I will discuss later in more detail (Chapter 1), they focus on technical and perceptual issues. Art historians have also been slow in breaching the gap. James Elkins, in *The Domain of Images*, admits that art historians need to expand their visual analytical domain beyond traditional, fine art subject matter and embrace new subject areas such as science, commerce, and technology (1999). Barbara Stafford in *Good Looking: Essays on the Virtues of Images* emphasizes this research deficit in imaging studies: "In a world literally raining images—whether pouring out of museums, channeled through television, video, software programs, and digital disks, or streaming from multimedia monitors and optical displays—neither traditional nor new art histories have emerged as practical guides" (1996, pp. 86-87). In addition to this call for an analytic shift in art history, we see an expansion of imaging research imperatives in the context of human consciousness (Ascott, 2003, 2006; Stafford, 2007) and epistemology (Goldberg, 2001).

37

To the knowledge of the author, no arts scholars have embraced computational scientific visualization, especially that which is used for mass public outreach. To educate the scholarly arts community about this aesthetic medium, this thesis reverse-engineers the process of creating computational scientific visualizations. To share the value of the field and provide new knowledge about our scientific, digital, and visual culture, it leverages theoretical studies in other domains that include visual metaphorical mapping, theories of evolution, and the science of emergence.

As members of post-industrial, Western societies--as experiencers of and contributors to the "information age," the "age of the internet" and of the "consumer"--we inhabit image-glutted cultural landscapes. We learn to see before we learn to read, and we learn to read images as well as text, if not better. Info-visualization is a way of organizing the incoming, "kaleidoscopic" flood of perceptions and concepts. "Quantity" is a concept that we use daily, and quantifying physical experience for cognitive ends is important to organizing our conscious world. We want to understand what proportion of people die at our age, how many calories affect our bodies, how much gas will cost, and what fills our cup. Our motive for understanding information in visual form goes much beyond academic inquiry. The graphical display of quantitative information is important to both the individual and society. Understanding the full implications of this data visualization praxis is necessary to our evolution and provides an expanded view of who we are and where we are going as a species.

Data visualizations, including scientific ones, increasingly feature as important elements in our cultural landscapes. To become culturally literate, we need to understand what they are and how they function semantically and semiotically (Kallick-Wakker, 1994). The primary goal of the visualization community is to help generate insights for decision-making. In a general sense, visualization can be defined as the mapping of data to

a representation resulting in a digital, sensory model--primarily a visual model. This mapping transforms numerical or symbolic information into visual information that people can use to understand, document, synthesize, analyze, hypothesize, and communicate. The transformed data includes a system of numbers that provides measurable, quantitative information and may also include computational and scientific models; sensor output from instruments; and geographic, statistical, and contextual information (Ellson and Cox, 1988; Anderson, 1989; Keller and Keller, 1993; Cleveland, 1993; Rosenblum et al., 1994; Ebert et al., 2000; Kniss et al., 2002; Woolman, 2002; Gaither et al., 2005; Chen et al., 2008). In what is perhaps a mark of materialist fundamentalism within data-viz practice, these graphic representations are commonly referred to as "data-driven," because they are derived from often abstract and complex numerical data and its structuring, rather than from the less mediated and more directly observed phenomena used by artists to create such non-data-driven visualizations as hand-drawn scientific illustrations. Yet, we ought instead to think of scientific visualizations as driven only partially by data: the mapping process still allows room for aesthetic manipulation and artistic agency. The models visualized from data are displayed using qualitative as well as quantitative information. Because the models represent data qualitatively, artists working in this domain gain a relative autonomy from the base assumption of mimetic representation.

Data visualization can be divided into two broad areas that employ advanced, three-dimensional (3D), computer-graphics imaging (CGI), synthetic techniques to display data-driven, quantitative and qualitative information: information visualization and scientific visualization, with which I am concerned hereafter. The two areas have much in common: both are informed by dynamic and static data and both involve mapping one domain of symbolic information onto a digital visual model. They share important methods in common when they process numerical data. They are both concerned with issues of

mapping information, reducing visual complexity, and 3D-CGI synthetic modeling and rendering. The main distinguishing factor between these areas is the nature and source of their data. Information (or data) visualization includes data analysis and presentation across a variety of disciplines, including science, medicine, engineering, geography, business, and finance (Card, MacKinlay, and Shneiderman, 1999; Ware, 2000). Scientific visualization mainly provides visual models of natural phenomena that humans recognize, such as galaxies, fluid flows, and thunderstorms (Rosenblum et al., 1994) (Figure 1). Information visualization provides data-driven, graphical models to represent abstract information such as demographics, statistics, genomics (Figure 2 and 3), and descriptive databases (Card et al., 1999; Ware, 2000). In contrast, scientific visualization, such as computerized, axial tomography (CAT) in medical imaging produces results in digitized slices of data that can be reconstructed into 3D digital visual models.

Figure 1. Scientific visualization of a natural phenomenon, a severe thunderstorm. The underlying computational data is structured.

Figure 2. Information visualization of NCSA genomics visualization project. The underlying unstructured data is organized into phylogenetic tree structure (white on black).

This bifurcation in visualization research is reflected in the IEEE Visualization conference structure, which now provides a separate track for Information Visualization.

Modern, scientific information visualization is rooted in the genesis of computer

graphics imaging that occurred in the 1950s: a technology developed sometimes in parallel

by, but also often in complement with, scientific institutions and the entertainment
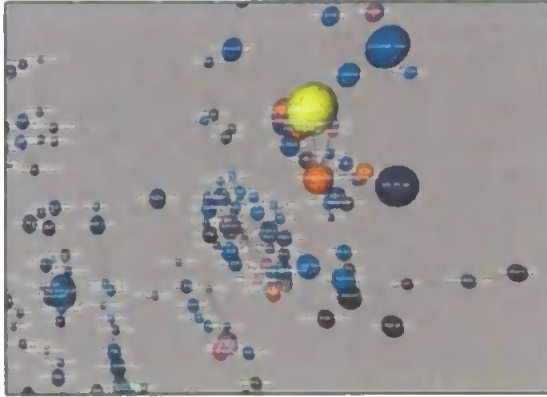
Figure 3. Information visualization of an NCSA visualization of a relational text database of unstructured data.

industry. The dawning of computer science as a formal discipline in the 1970s and the formation of supercomputing centers in the 1980s further galvanized research communities, making possible the advanced graphic simulations and visualizations we have since achieved

(McCormick et al., 1987; Friedhoff and Benzon, 1989; Brown, 1989-1990). As Roger

Malina writes, "The twin methodologies of scientific visualization and computer

simulation have emerged as essential approaches in dealing with phenomena accessible to

the human senses only through their extension, amplification, or augmentation" (2006, p.

49). Scientists and decision makers routinely employ digital, data-driven visualizations in

an attempt to understand the plethora of data and mathematics being generated by

observations, supercomputer computations, instruments, and sensors. "Together with

theory and experimentation," Dan Reed writes, "computational science now constitutes the

"third pillar" of scientific inquiry, enabling researchers to build and test models of complex

phenomena–such as multi-century climate shifts, multidimensional flight stresses on

aircraft, and stellar explosions–that cannot be replicated in the laboratory, and to manage

huge volumes of data rapidly and economically" (2005, p. 1). For Reed, computational

science is not just about large-scale data and raw computational speed, it is the virtual

laboratory for phenomena that humans cannot prove at an experimental level:

41

> "But raw computation speeds represent only one facet of the third pillar. Computational science enables researchers and practitioners to bring to life theoretical models of phenomena too complex, costly, hazardous, vast, or small for 'wet' experimentation. Computational cosmology, which tests competing theories of the universe's origins by computationally evolving cosmological models, is one such area. We cannot create physical variants of the current universe or observe its future evolution, so computational simulation is the only feasible way to conduct experiments." (p. 13)

CGI visualization is the only virtual view into this digital laboratory. Yet, such visualizations also deluge our popular visual culture and have a broad cultural impact through all technologies of reproduction and transmission, from the periodical press to virtual-reality games.

In this thesis, I focus on the circulation of scientific, data-driven visualization within popular culture, rather than on its use as a mode for scientific experimentation--a topic that merits its own, extended treatment. As a means of scientific communication for popularizing theories, hypotheses, and conjectures to near disciplines as well as lay audiences, digital, data-driven visualizations have come to permeate society; they have become an important part of visual culture. Large audiences view them on television, at the movies, and in immersive, digital-planetarium shows. Well-respected, scientific journals such as the American *Science* and the English *Nature* and popular magazines such as *National Geographic* regularly feature these visualizations of scientific thought. They are powerful informants due to the scientific and technological authority they wield. Within modern societies, they originate and perpetuate essential strains of our cultural imaginary, those that have come to depend on scientific narratives. In this way, they act as powerfully to shape culture and its developments in our post-industrial societies as mythological artifacts once did in pre-industrial ones. In a very real sense, they help to construct our modern mythologies, those that can never be experientially proven (Jung, 1959), especially those that rely on the scientific saga of the creation of the universe.

I am particularly interested in computational scientific visualizations' and their

metaphorical and cultural interactions. Scientific communication employs visaphors to

represent simulated theories and hypotheses of material phenomena for scientists, but

through science education also proliferates and culturally reinforces these concepts to the

public. Visaphors are distinguished from other types of visual metaphors in that they are

rendered digitally from numerical data. To concrete representations, they map data that are

founded upon and derived through compound, disciplinary assumptions (such as in the

field of mathematics), systems of information, models of science and approximation

methods (Oreskes, Shrader-Frechette, and Belitz, 1994; Hesse, 1996; Hallyn, 2000; Lakoff

and Nunez, 2000; Nunez, 2000; Reed et al., 2005). Visaphors also differ from other hand

or digitally illustrated visual metaphors because of their specialized computational and

quantitative nature. They provide twenty-first century maps of uncharted numerical

territories (Bertin, 1983; Harley, 2001; Akerman and Karrow, 2007). The media that are

used to manifest these visual metaphors—advanced computer graphics technologies—and

sometimes to display them—such as planetarium digital domes--further impact their

potential for artistic manipulation, means and modes of production, and audience

interaction (Berton,1990; Crary, 1990; Ascott, 2003; Sherman and Craig, 2003; Bowman

and McMahan, 2007; McConville, 2007). To create visaphors, the visualization artists

incorporate aesthetics as an inherent part of a very complex process where data has been

mediated and filtered and is used to communicate scientific theories. Their aesthetic power

is grounded in their representation of embodied metaphorical mappings and the systemic,

epistemological structures that inform them and are informed by them (Lakoff and

Johnson, 1980, 1999; Cox, 2006).

As my primary argument, then, I appeal to the data-viz community to broaden our

view of the power and purpose of the visaphors we create. Historically, we have located

their value in their ability to clearly and accurately translate and represent data, or in their capacity to convert computational, scientific models into visual forms. That is a view I once held. I have come to find, however, that as a new, artistic medium visaphors have the potential to generate insights into humanity's previously unsuspected evolutionary capacities and contribute to a deeper understanding of our place in the universe (De Chardin, 1959; Margulis, 1986). Visaphors function alongside other metaphoric knowledge maps to provide epistemological scaffolds that enable us to both express and experience a sense of reality that is always already a socially embodied construction. They empower us to interactively participate in collective, cybernetic, autopoetic systems (Ascott, 1968, 2001; Maturana and Varela, 1980, 1987; Packer and Jordan, 2001). Our self-conscious interaction with these systems contributes to the evolution of our greater consciousness. Through this enlightened position, we become fully able to appreciate the impact of the scientific visualization arts. We gain insight into how the audiences who engage with our community outreach efforts interact with, enact, and recycle visaphors as well as into how the visaphoric aesthetic emerges from our collective, symbiotic brains as an evolutionary, bio-cultural, technological phenomenon.

I continue to value the contributions data-viz makes to scientific practice and popular science education (Gordin and Pea, 1995; Davies, 2008). I continue to support the data-viz field's sense of best practices, employing many of these techniques today. In fact, these practices reflect the natural process of generating consistency, facilitating learning and rapid comprehension. However, I have also come to believe that the current goal of scientific and data visualization--to reveal an objective universe through the absolute, accurate translation of data—is an illusory one. I have lost faith in this positivist mission, having now accepted the argument that all data and information is mediated and filtered in some way: instrumentally, computationally, or interpretively. Rather than lamenting this

44

contingency, I celebrate the potential for empowerment that this awareness provides to anyone working with visualization systems. I write this thesis in order to make a case for how our work goes beyond the ways in which we have previously understood our endeavors. I encourage us to embrace a novel exposition of the power of visaphor art to reveal emergent properties from science and to be an emergent property of culture.

This argument brings a new perspective to the entire visualization production process, one that is collaborative and enables great synergies. It portrays the production of visaphors as a collective activity undertaken by the creative, interdisciplinary, research colony of the Renaissance Team, whose activities go well beyond the more functional and capital-driven ends of commercial art. Created by directors, managers, designers, scientists, and technologists, the visaphoric arts employ some of the most advanced, high-performance technologies of science today, for cultural as well as scientific ends. Visaphors possess a collective power--not in spite of collaboration, but because of it (Bermudez et al., 2005; Prophet and d'Inverno, 2006; Sandin et al., 2006). From hybridity and diversity, they germinate and gather strength.

This argument also brings a new perspective to the outreach and dissemination process for the visaphoric arts. They have the potential to communicate much more than basic science education and promotion (Gordin and Pea, 1995; Davies, 2008). As a result, this emerging art requires an expanded distribution space beyond traditional art exhibitions or even the Hollywood entertainment industry. I have worked to deliberately expand the reach of visaphors to science museums; educational IMAX films; large-scale television projects; digital domes; and far-reaching, distribution avenues such as internet TV. This proliferation interacts with the embodied minds of millions, the amalgamated collective, gaining maximum impact within our visaphorically reinforced sense of "reality." In particular, I use visaphors to expose emergent properties of complex systems of both

45

meaning and matter, showing how emerging patterns of systemic interdependence and cooperative exchange run right through evolution.

Visaphors are a distinctly modern, advanced-technology art. They have a special relationship to modern computational scientific models, but the processes that yield their construction and comprehension are set within a wide historical discourse that concerns the nature of reality and the metaphorical and scientific processes used to engage with it. From the field's inception, visualization experts have been predisposed toward scientific materialism. Yet, I have found convincing the constructivist challenges to this position, especially as they have been expressed within metaphor studies and its correlates within cognitive science (Rosch and Lloyd, 1978; Varela, Thompson, and Rosch, 1991; Indurkhya, 1992; Lakoff and Johnson, 1999; Stafford, 2007). The epistemological shift I have made and hope to convince other to make enables a different view of data-informed visualization and scientific mathematical models. I exploit this new perspective here to reveal the complex processes of cognitive and social construction through which visaphors emerge and operate. In a profound, new way, the visaphor aesthetic awakens our visual appreciation of the inherent beauty and symmetry in cosmological models and scientific simulations, marking a hybrid path in our cultural evolution.

Visaphors themselves are emergent properties within a self-sustaining visual metaphoric feedback system, which enables viseotelecommunion. This cybernetic process reveals itself in the visual history of our mythologies and in the scientific creations of today. Visaphors enable us to participate in the self-conscious building of mythological scaffolds, from our modern technology perspectives, enabling us to evolve new, metaphorical territories. Visaphorizing is a self-conscious aesthetic that enables us to participate in a new kind of scientifically-based mythology, one that continues to cut its stories from the fabrics of existence and to enable cosmic discoveries, universalized

46

ontologies, and existential explorations. Viseotelecommuning, in this case through visaphorizing, is a process of the universe looking at itself, collectively reflecting upon its own evolution.

Visaphors operate within a field (Ascott, 2006), reaching deep into human consciousness, providing a clear marker of our symbiotic brain and the evolutionary processes of consciousness. Visaphors both enable an exposition of this universal process and benefit from this evolution of our embodied realities (Maturana and Varela, 1987). They reveal how the universe is not made up of discrete phenomena, but multiple layers of systems that emerge from individual components. I have felt myself to be a part of this extraordinary, bio-cultural, technological evolution. Visaphors are a celebration of who we are in the universe; they help us negotiate our embodied nature. Such an art form has the power to inspire us to reevaluate our place in the larger universe: our evolution, our interventions, and our unsuspected capacities.

The argument is organized as follows:

Chapter 1 makes a case for evolving the view of scientific visualization from a practice that represents reality to one that constructs it through digi-epistemological aesthetics.

Chapter 2 describes the collaborative and technical process I pioneered for creating visaphors--demonstrating that this process is inseparable from the resulting visaphors' aesthetic, epistemological, and ideological dimensions.

Chapter 3 establishes a ground for understanding the interactive dimension of visaphors through explaining how metaphors are made and understood through cognitive, rather than purely, linguistic processes. I use this ground to argue that visaphors construct and are constructed by a viseotelecommunion between our embodied minds and our contemporary, scientifically-authorized social myth of reality.

47

Chapter 4 elucidates the philosophy of science tradition out of which visaphors have emerged to provide a basis for my argument that visaphors are specially suited to visually theorizing emergence because of the nested, self-generating systems they portray. A constructivist account of scientific knowledge is championed over the positivist and empirical theories that have historically validated the mission of data-viz. This account is rooted in a minor tradition (i.e., De Chardin, Varela, Margulis) that elaborates new evolutionary processes, including cooperative, autopoetic systems and their apprehension through an expanding human consciousness. The justification of this tradition provides a new and different basis for authorizing a broader mission for the visaphor arts, since I claim that visaphors and the technologies that support their creation and proliferation are natural extensions of these evolutionary processes.

Chapter 5 describes how visaphors have inherited the conventions of invented communications systems historically, politically, and technologically in order to expose the mechanisms that make artistic intervention in the form possible as well as their cultural significance. Special attention is given to visaphors' adoption of cartographic conventions, as visaphors and maps both engage in mapping processes. The final section of Chapter 5 relates the function of visaphors to historical mythologies and archetypal forms. Visaphors narrate our contemporary societies as historical mythologies once did ancient cultures, populated with fanatastic chimeras of art, science, and technology. Visaphors evince a powerful worldview, one of many possibilities.

Throughout the thesis, I illustrate concepts in the scientific visualization arts--from design to production to final product to reception and interaction--with examples drawn from my own body of work. I focus especially on those projects provided in the **Practicum**.

Chapter 1:   The Evolution of Scientific Visualization: Shifting Paradigms from Representing to Constructing Reality

Scientific visualizations differ from other types of scientific illustration in that they are intensively informed by digital data.   Computer-mediated visualization is a relatively young technology.   After the first vacuum-tube computers were invented during the middle of twentieth century (Greenia, 2000), data-driven scientific visualization developed in tandem with computer-graphics imaging (CGI).   A small portion of scientific researchers used these nascent computer technologies to model natural phenomenon.   However, CGI-synthetic methods were primarily exploited by the entertainment industry in the 1970s. Hollywood Director George Lucas invested in CGI research, resulting in computer image-synthesis algorithms that were enslaved to photo-digital realism and special effects cinema production.   Early CGI researchers published many of these foundational techniques in the SIGgraph (Special Interest Group in Graphics, Association of Computing Machines) conference proceedings (Machover and Hart, 1999).   However, the most advanced CGI algorithms remained the proprietary property of production companies.   Most basic research scientists did not have access to advanced CGI algorithms or graphics computers in order to visualize their complex numerical data.

It was not until the dawning of supercomputing that CGI-synthetic methods expanded to include techniques particular to advanced scientific computational challenges. During the last half of the twentieth century, the CGI raster-hardware industry matured, three-dimensional (3D) CGI synthesis software advanced, computational science expanded, and a community of developers coalesced around the burgeoning concepts of data-driven scientific visualization (McCormick et al., 1987; Friedhoff, 1989; Foley and Ribarsky, 1994; Rosenblum et al., 1994).   In 1985, the National Science Foundation (NSF)

established five academic supercomputer centers, and they embarked upon the task of making supercomputing and new technologies available for basic research, especially computational science.

By 1987, NSF had convened a panel to report on Visualization in Scientific Computing (McCormick et al., 1987). The report led to a major initiative in the research and advancement of scientific visualization. Eventually, Hollywood-style visualizations gave way to mathematically rigorous, interactive visualization software (Brown, 1989-1990). Over the last twenty years, data-driven scientific visualization has developed into a language with its own conventions and visual methods, such as 3D glyphs (Ellson and Cox, 1988) and interactive, progressive-disclosure techniques. By 1990, new conferences were devoted solely to research for visualization in scientific computing (Patrikalakis, 1991; Rosenblum et al., 1994; Chen et al., 1996). A particular power of scientific visualizations is that they need not be presented in isolation; researchers can use them to integrate scientific and contextual information into "smart" applications that combine descriptive and spatial knowledge discovery (Stoev et al., 2001; Peltier et al., 2003).

Perhaps, however, in reaction against the field's early artistic and entertainment-directed origins, most science publications discussing computing and supercomputing are given to advancing technical research and focused on mathematical algorithms that make computing more efficient or provide alternate solutions to existing technical problems: *ACM SIGgraph Computer Graphics Proceedings*; *IEEE Visualization Proceedings*; *IEEE Image Processing Conference Proceedings* (Munzner et al., 2006). This predominate professional orientation grew out of the first IEEE Visualization conference in San Francisco in 1990, for which I served as one of the organizers. Computational scientists and computer scientists attempting to understand simulation data pervaded the early days of IEEE Visualization; computer scientists specializing in computer graphics continue to

50

dominate the visualization field. The plethora of data, whether generated from computers or gathered observationally, has driven the growth and focus of the visualization field, leading its study and practice to center on converting encoded numerical information into technology-mediated visual forms that human beings can understand in order to make decisions. Until the last decade, the research mantra has been "better computer science algorithms." Now, applied perception, human computer interfaces, and data analytics promise to yield a better understanding from the onslaught of data. The onus of making "a good visualization" is on the expert in his/her transformation and display of the data, which is supposed to represent as accurately as possible some found reality.

The dominant computer science publications, when not focused on technical issues, have tended to focus on perceptual design approaches for information visualization (Gershon, 1990, 1994; Ware, 2000). In books such as *The Visual Display of Information and Visualizing Data* (Tufte, 1983), and the proceedings of IEEE Vis, the primary goal of visualization is to communicate information, pulling that information from data and presenting it in an objective perceptual form. In Colin Ware's *Information Visualization: Perception for Design* (2000), for example, the primary goal is to develop a science of visualization using a perception-based approach. Psycho-perceptual (e.g., optics, visual attention, spatial perception) and neuroscience discussions are used to consider design, interface, and problem solving. The role of the artist and designer is limited to clarifying information and providing consistent design strategies. Ware's work suggests a growing emphasis on perception studies in the scientific visualization field, a sense that although computer science and analysis algorithms are valuable and play an important role in scientific visualization, they are not necessarily the primary goal of visualization experts today, which is, rather, represented by this 2005 conference presenter in the field:

"With a large collection of developed algorithms and techniques at hand, visualization researchers are now coming to grips with the fact that it is not devising an algorithm that is the critical problem, but rather how to map data to display in such a way that people can see important patterns. In other words it is about perception." (Ware, 2005, p. 707)

Granted, over the years, more publications have begun to cover issues of representation in scientific visualization (Tufte, 1983, 1990; Cox, 1989, 1990, 1991; Lynch and Woolgar, 1990). However, their view of representation remains too restricted. Also worth noting is that the scientific visualization community has tended to focus on the development of its own practice as it impacts experts within the visualization and associated scientific communities, a significant bias in the field's theorization. The community's process of honing, selecting, and validating for general audiences in popular contexts is much less understood and well-defined. This is evidenced by the overwhelming number of data-visualization publications devoted to technical issues rather than epistemological ones.

Even as late as the 2005 IEEE Visualization conference, discussions of the future of visualization focused on the use of "good" design practice to guide visual techniques and methods to evaluate visual techniques. One contributor noted in the proceedings, "One of the enduring fundamental challenges in visualization research is to determine how best to portray a set of data so that the information it represents can be accurately and efficiently understood. Both design and evaluation have key roles to play in this process" (Interrante, 2005, p.706). To me, this suggests that artists and designers are still valued as playing a role in providing additional visual tools for the scientist, a claim I made in favor of interdisciplinary collaboration as early as 1985 in order to make a case for the contributions of artists and designers within the field. We now see more artists participating in the field of informatic arts than ever before (Wilson, 2002). Few visualization conference researchers, however, have expanded upon historical, political, or

other humanistic issues (Kallick-Wakker, 1994; Manovich, 2008). Without a doubt, my contributions to the outreach of scientific visualization have led me to become concerned with their importance as cultural and humanistic phenomena.

The assumption that we are discovering objective truth in data rather than both serving as and engaging with active participants in constructing meaning through metaphorical thinking does not support most of the research agendas described above (Kallick-Wakker, 1994). The positivist perspectives of funding agencies, such as the National Science Foundation (NSF), influence visaphor definition, creation, and presentation. As a result, data-viz primary research publications and conference agendas remain narrow. To my knowledge, within standard scientific visualization discourse, cognitive conceptual metaphors and cognitive networks are not attended in the context of making or interpreting data-driven visualizations within conferences such as IEEE Visualization Conferences, where the focus is technical: efficient algorithms or perception issues. The mainstream of the visualization community has dedicated little discourse to the deep philosophical traditions underlying visual metaphorical understanding, concomitant cultural biases, and cognitive conceptual networks that influence the interpretation of the human-in-the loop.

The design and evaluation, the creation and consumption of visaphors is an iterative process across the visualization community, which has established the goal of rendering self-consistent visual metaphors. As is the case with linguistic metaphors, when visual metaphors are used more consistently, they move across the metaphoric continuum from the conventional to the novel (Indurkhya, 1992). To gain currency, visaphors require "buy in" and common use. Over the past twenty years, visaphors have developed their own self-consistency, or conventionality. Their continuity is based upon the community honing their consistency through approval and use. That approval is framed in terms of

applied perception research: "My bottom line is that visualization researchers are in the applied perception business whether they know it or not" (Ware, 2005, p. 708). The basic assumption behind this tenet is that visualization experts are discovering an objective reality rather than participating in its cognitive construction.

I grant that the mainstream visualization community has engendered important research in using this approach, yielding successful results in areas such as the comparison of multivariate datasets from different sources and the development of computer graphics techniques for feature extraction, graph fitting, and visual probabilistic inference (Cleveland, 1993; Kaufmann et al.,1993). At the beginning of my research as a visualization artist in the 1980s and 90s, I approached the visual display of quantitative numerical data in much the same way in which the visualization community continues to direct research. Early on, I pioneered with Kodak researcher Dr. Richard Ellson the 3D-CGI representational technique of using glyphs to indicate elements (such as direction and temperature) in scientific simulations (Ellson and Cox, 1988). Over the years I have directed my team to develop and use advanced graphical techniques from research as a part of our visualization process and pipeline. My main objective was to take the numerical data as information and encode that information into digital graphical displays to aid humans in the understanding of data so that they could analyze and reason about it. I have been very successful in working with scientists and helping them to discover new aspects of their computations through our visualization process (see Drs. Brian O'Shea and Michael Norman's letters in Appendix).

Yet, after twenty years as a scholar and artist in the data-viz arts, I have come to view visaphors as more than the accurate representation of data, and I hope to encourage this expanded view within the field for artists, scientists, and computer scientists. I now recognize that data-viz cannot fulfill the illusory aesthetic goal of hard realism: to

objectively portray the external as it is, with no biases or altering interpretation. I

understand the assumptions behind the numerical heuristic models, the contingency of

much data, and the paradigmatic perspectives through which they are visualized. Rather

than mourning the loss of this surety, I have come to recognize that we create meaning

through our conceptual metaphorical maps (discussed in Chapter 3). The construction and

consumption of visaphors is a process of finding our place in the universe; it is a part of

our collective cybernetic process (discussed in Chapter 4).

Acknowledging the constructed and aesthetic nature visaphor is not to say that the

data-viz community's perceptual understanding of visaphors and related best practices for

creation are irrelevant or minimal in value. The visaphors that flourish are those that are

fueled by their consistency and usefulness. It is to say, however, that visaphors can and do

offer us more when we expand our account of them, awakening our philosophical

awareness and artistic vision. To make the most of this potential, the data-viz community

and imaging scholars need to learn more about how visaphors draw upon cultural and

psychological constructs and, through their public outreach, are re-inscribed and re-

circulated by general audiences. In some sense, data-driven scientific visualizations are no

different from other forms of art in employing visual conventions, maneuvering within a

visual rhetoric, and expressing (some degree of their) informational and (to a larger extent

their) emotional content metaphorically, iconographically. Yet, we also need to consider

how visaphor, as a special form of aesthetic practice, contributes to human experience.

I believe that visaphoric art reaches deep into human consciousness, providing

more than just an effective, objective display of information. Even in terms of perceptual

theories of visaphor-processing by audiences, the data-viz arts need to explore how,

because of their special relationship to a modeled external real, visaphors may in fact be a

result of our perception that is being mediated by higher-order consciousness and

unconscious perceptual states. For example, the common experience of driving a car on "automatic pilot" while not being consciously aware of traffic illustrates one of these unconscious perceptual states (Carruthers, 2007). Lynn Margulis and Dorian Sagan's definition of the human brain as symbiotic suggests that the very conduits of our consciousness are constructed by autopoetic systems. They ask whether it is

> "so farfetched after all that bacterial symbionts created biospheric information pathways as important as quantum mechanics or the theory of relativity? In a sense we are 'above' bacteria, because though composed of them, our power of thought seems to represent more than the sum of its microbial parts. Yet in a sense we are also 'below' them. As tiny parts of a huge biosphere whose essence is basically bacterial, we--with other life forms--must add up to a sort of symbiotic brain which it is beyond our capacity to comprehend or truly represent." (Margulis and Sagan, 1986, p.152)

Pattern recognition is more than the clear and accurate indication of patterns on a visual display, the goal of good scientific visualization technique. I believe with Margulis that our ability to create and transmit patterns, as well as to perceive them, is a marker of our symbiotic brain, which---through metaphor--conceptually networks our embodied experiences (our sense of materiality) with present and historical human cultures. Patterns denote significance, and, at the same time, achieve significance through denotation. We experience them as embodied, metaphorical maps that, when we reflect upon them, expose the nature of our own embodied reality. Thus, when we evoke patterns in our art, we are not just conveying information; we are exposing what we assume coheres and the forces and processes that achieve coherence (as I discuss in Chapter 5). We are revealing the cognitive construction of our visaphorical reality. Visualization is our consciousness reflecting on itself, and is an extension of ancient life processes injected into our most advanced technologies. Of this macrocosmic impetus to evolve consciousness, Margulis and Sagan write:

> "In one of life's giant, self-referential loops, changing DNA has led to the consciousness that enables us to change DNA. Our curiosity, our thirst to know,

56

our enthusiasm to enter space and spread ourselves and our probes to other planets and beyond represents part of the cutting edge of life's strategies for expansion that began in the microcosm some three-and-a-half billion years ago. We are but reflections of an ancient trend." (1986, p. 22)

We are not driven merely to survive in the most limited and physical sense, but to discover and experience, to understand and know.

Yet, this adaptive strategy is creative and potentially innovative, not just reactive. The complex interplay of our collective, symbiotic brains plays a role in our making sense; we create sense rather than merely finding it. When we create visaphors, we are not just transforming numerical data into encoded bits of information for humans to perceptually consume. Visaphors operate and reveal social and cognitive interactive processes; much like an iterative fractal mathematical function or an iterative Escher drawing, they provide a cybernetic feedback mechanism that reinforces their generation while revealing the process (Wiener, 1954; Ascott,1968; Heims, 1987), what I will later discuss as viseotelecommuning (in Chapter 4). Visaphors engage viewers in a process of active participation, of semantic and, more specifically, semiotic co-creation.

Visaphors are useful in deepening the human experience through connecting us with our collective, or field, humanness, and providing a technoetic pathway to a deeper self-knowledge (Ascott, 2006). To this end, the numerical data of computational science may be seen, for instance, as revealing truths of the universe not so much in terms of their accuracy in delineating natural phenomenon but in their mystical revelations of cosmic, universalized ontology and the existential explorations it enables (Kauffman, 2008). Such an art form, with its potential for re-envisioning the "whatness" of our existence, inspires us to continue to evaluate our place in a larger created, how we are evolving, and how we can intervene in our nature and its potentialities. In this sense, a self-conscious visaphor aesthetic can help us to commune with our humanness, as a collective reflection and not

57

merely as (what Morrison defines) as a 'cognitive art' (Tufte, 1990, p. 9). Visaphors reflect our evolving collective consciousness. They are tangible artifacts of our meaning-making that serve to both suspend our disbelief as well as generate new meaning, novel faith.

The most valuable aspect of the new visaphor aesthetic I propose is its power to awaken our cognitively and intuitively enlightened selves, granting us insight into our as yet unsuspected capacities. Data-viz's collective cosmological models and scientific simulations embody a hybrid reality—mathematical and cultural--that we compose, manipulate, and employ, one that generates rhythm, symmetry, and beauty on its own terms, and not just in mimicry of a supposedly unmediated natural world. Visaphors are hybrid art forms that emerge from the complexity of our modern social systems that are formed, in part, through our advanced technology. These hybrid art forms narrate our contemporary societies as historical mythologies once did ancient cultures, populated with fantastic chimeras of art, science, and technology. The supercomputer data models that we ourselves determine are yet another component of the complexity of our universe. As we might appreciate the glorious diversity and awesome power in nature and its complexity, we may also appreciate the power and complexity of the process of making and consuming visaphors.

We should make it our mission to participate self-consciously in the building of such mythological scaffolds, which--from the perspective of our modern, technologically advanced community--stage a new mythology. Although the dominant secular mythology of today is the Story of Science that capitulates to Enlightenment values, we can self-consciously reinscribe it to express more contemporary values that go beyond anthrocentricism and a competitive view of relationships to and within nature. Constructed by collaborative and diverse Renaissance Teams from interdependent autopoetic systems,

58

visaphors become an ideal medium for embodying this Environmentalist Story of Science. Visaphorizing marks a thread in the course of human evolution, another path on the way to understanding the deeper meaning of existence and being. It takes its place among the making and consuming of great historical artifacts in the history of humanity, from the fertility goddesses of 5000 B.C.E. left quietly in their hidden shrines to the most virtual embodied experiences that are vividly displayed in today's digital cathedrals of science (Gadon,1989; Baring and Cashford, 1993). Visaphors play a part in our symphonic, conscious evolution. Like the pre-modern myths they resemble, they persist as the collective cultural property of humanity, evolving new metaphorical territories.

Chapter 2: Scientific Visualization Arts: Collaborative Methods, Data Transformations, and Design Strategies

The basic process for creating art using conventional media, such as oil paint, is no doubt well known to educated and art-savvy readers. Since the process for creating this relatively new form of computer-support, data-driven art is not, I spend the following chapter elaborating on the collaborative, technical, and design aspects of the artistic process for working in this medium that I have played a significant role in pioneering. As I have suggested earlier, many of these technical aspects are not separate from the making of meaning or construction of knowledge that informs the creation of visaphors and—perhaps, ultimately, their reception and recirculation. Even as I describe the more concrete dimensions of creating visaphors, I will elaborate how the technological and interdisciplinary construction of visaphors within a particular industry, with its own usual bases of funding, impacts the art of data-driven scientific visualization. I am especially interested to show how the work visualization artists do with data demonstrates its contingency and, ultimately, its representational plasticity.

Renaissance Teams and Cybernetic Partnerships: The Data-Viz Workshop

From the European cult of the individual and its Romantic view of exceptional, imaginative genius, we have inherited an image of the lone artist who creates in isolation within an impoverished studio, moved to express a personal vision that may remain poorly understood until someone recognizes his vision (the pronoun is meaningful). However, the laboratory-driven environment of scientific visualization--in which artists, scientists, technologists, and technology work in partnership—shows how limited and limiting this model can be (Varnedoe and Gopnik, 1990; Cox, 1992, 1993; Shanken, 2005). Since

1985, I have collaborated with scientists and computer technologists to visualize scientific data from supercomputer simulations at the National Center for Supercomputing Applications (NCSA) at the University of Illinois at Urbana-Champaign. I coined the term "Renaissance Team" to describe the team of specialists, including artists and designers, who collaborate to solve problems in the visualization of data (Cox 1988a, 1988b). The complex informational, aesthetic, and technological demands of creating visaphors often require the expertise of many people (Brown, 1989-1990; Cox, 1990, 1991, 2000, 2003a, 2003b; Foley and Ribarsky, 1994; Prophet and d'Inverno, 2006; Sandin et al., 2006). For *Unfolding Universe*, which first aired on the Discovery Channel in June 2002 (Kahler et al., 2002; Cox, 2003b), for example, we created over seventeen scenes using data from five scientists and several different rendering applications. Research to automate the design process has been limited and often intended to integrate design into the software pipeline (Brown, 1989-1990; Robertson, 1991; Ribarsky, Ayers, and Mukherjea, 1993; Beshers and Feiner, 1994; Kruger, 1998; Ware, 2008). One can see in contemporary science this movement toward collective problem-solving.

When well coordinated, Renaissance Teams ensure that the one does not get lost in the many. Rather, the one is encouraged to find its own, unique contribution to the whole. The complexity of this bio-cooperation can build layer upon layer in overlapping autopoetic systems, such as Margulis and Sagan describe:

> "An organism constantly exchanges its parts, replacing its component chemicals without ever losing its identity. This modulating, 'holistic' phenomenon of autopoesis, of active self-maintenance, is the basis of life; in order to preserve key aspects of their identity within their boundaries and respond to the challenges of self-preservation." (1986, p. 56)

From the moment in my scientific visualization practice when I began to take on complex, large-scale problems, I realized I could not thrive through working in isolation. I conceived of Renaissance Teams as a means of meeting these demands, drawing upon

what I now understand as evolutionary collaborative tendencies. Initially in my work as a computer artist, I had regarded the computer as a partner. Today, I see the computer as a powerful electronic enabler, but the true collaborators are the people with whom I work. To echo Margulis and Sagan, Renaissance Teams are active organisms in the constant process of exchanging parts and co-participating in the recombination of creating the visual imaginary. A collective group with a diversity of expertise is both autopoetic and forward-thinking. Renaissance Teamwork implies a symbiotic process, one that is especially crucial for artistic production within unconventional settings, which is the case with aesthetically-oriented scientific visualization within scientific domains. The strategy makes especially good sense as a long-term approach for interfacing creative cultural workers, their expertise and products, with those of scientific ones, who are better funded and institutionally sustained. Margulis and Sagan reason that "superficially weak organisms have survived in the long run by being part of collectives" (1986, p. 124). Yet, the power of Renaissance Teams is not only in their collective nature, but also in their hybridity: they reach across disciplinary boundaries to form mutually beneficial processes and outcomes. Because of the effort's hybrid cooperation, the outcome of the team's collaboration is greater than its decomposable functions (Cox, 1991, 2003, 2006).

A challenge for the arts community may be to see workshop environments and their creative products as viable artistic research efforts, rather than as compromised by commercial or, especially in this case, academic disciplinary interests that reduce the work to the purely informative and functional. Collaboration is central to many art-technology endeavors such as filmmaking and the performance arts. Since the 1960s, artists and scientists have collaborated in research laboratories for research, demonstration, and art (Knowlton, 1965), producing technological innovations as well as creative digital films. Bell Telephone Laboratories researchers invented the first computer-produced movies,

using computer-controlled display tubes on an automatic microfilm recorder to generate moving images. Since those early experiments, new high-tech research environments for data-viz have evolved, providing new models for collaboration in academia and industry. Edward Shankin has reviewed a variety of research institutions and universities that now house facilities and provide funding for artists to work on interdisciplinary, collaborative teams in tandem with scientific and technical researchers. For example, the Canadian Banff New Media Institute, Austrian Ars Electronica Center, and Swiss Artists in Labs program provide fertile, interdisciplinary research environments. Shankin confirms the expansion of these interdisciplinary centers, affirming that the "European Union (EU), local governments and advanced scientific research centers in Europe continue to provide substantial support for interdisciplinary research involving artists at full-service media art centers, museums, exhibitions and symposia, and in partnerships with industrial and academic research programs" (2005, p. 415). In *Degrees of Freedom: Models of Corporate Relationships*, Sara Diamond outlines promising collaborations that have led corporations to explore new models of funding for art-technology-scientific innovation (2005). The promising trend toward facilitating this type of collaborative environment is also expressed by such research collaboratories as (art)n in Chicago (Sandor and Fron 2002), SmartLab (2008) and USC Institute for Creative Technologies (2008).

These collaborative technological explorations bring into sharp relief many issues of and opportunities for funding and copyright. Trans-domain research investments have led digital artists working within such collaborations to challenge copyright vagaries and to negotiate intellectual property rights in new ways (*Harvard Law Review*, 1994). Some of the new funding models being attempted are more successful than others, but clearly it is necessary to have funds to fuel the development of high-technology, interdisciplinary experiments. To encourage this development in the U.S., in 2007 the National Science

Foundation (NSF) developed an experimental new funding opportunity for interdisciplinary collaboration among creative practitioners and computer scientists: CreativeIT. An important reason for this increased investment in data-viz is the general recognition that huge problems, such as climate change, require resources at multiple institutions and the expertise of many disciplines to explore and attempt to solve them (Reed et al., 2005).

Large creative productions for public venues such as a digital, full-dome planetarium show or PBS NOVA high-definition television show likewise require the expertise of a diverse collection of talented individuals: artists, designers, educators, writers, actors, and producers. In addition to working collaboratively with such groups, the data-viz artist who runs a workshop needs the management and production skills to realize complex and coordinated artistic visions. Negotiating issues of funding, intellectual property, and collaborative etiquette among team members requires special skills. I have played a critical role, for example, in NCSA / University of Illinois participation in *The Black Holes Project* by negotiating contract, copyright, royalties, and intellectual property issues with the University and museums. Without these contributions to *The Black Holes Project*, the scientific visualizations of supercomputer-based computational science would not have been possible. Thus in data-viz, the aesthetic practice of artists is intertwined with their roles as project managers, directors, technologists, and researchers. In the collaborative-arts industries, these skills are qualities assigned to the "producer."

The idea of artist as "producer" can be related to Russian constructivism in the 1920s and its sense of the revolutionary and political function of the artist within an industrial environment (Gough, 2005). The Russian constructivist movement included artists like El Lissitzky and Laszlo Moholy-Nagy, who promoted the idea that the most important art was produced for socially salutary purposes. The constructivist artist was

65

viewed as a producer of social change who required practical skillfulness, ranging from industrial design to production management. In expansion of these ideas, Walter Benjamin has explicitly argued that technological change alters the operation and social impact of the artist or author as producer (1979). He explicitly couples technology to political change: "technical progress is for the author as producer the foundation of his political progress" (1978, p. 230). Benjamin focuses attention on photography; I extend these artist-as-producer and politico-technological relationships to the more advanced technologies and computational science of visaphors as collaborative and post-industrial art forms that have social-politico impact.

At the same time, creative industries coupled with the revolution in digital information technologies and trends in mainstream popular culture have codified the role and process of artist-as-producer. In *High & Low: Modern Art and Popular Culture*, Kirk Varnedoe and Adam Gopnik argue that "the story of the interplay between modern art and popular culture is one of the most important aspects of the history of art in our epoch" (1991, p. 19), tracing the impact of creative industries such as advertising, mass media, comics, and other "low" forms of art. In the collaborative, entertainment arts, the producer plays a pivotal role. Film, music, television, and similar productions require different levels of artist-as-producer responsibilities, ranging from project initiation to project direction in all phases of production. These creative productions require teams and collaborative methodologies in which the role of artist-as-producer is codified not only as a function of politics and technology, but also of the artistic process across culture. I extend these ideas to include the impact that digital immersive and scientific computational technologies have had on the role of artist-as-producer and the collaborative methodology used to create and distribute visaphors. For example, in large-scale collaborative outreach projects such as *The Black Holes Project*, the artist-as-producer orchestrates teams and

66

creative processes. The artist-as-producer must take into account creative impact across the public domain, too, since, as I argue in following chapters, such projects spread through culture beyond mere educational intent.

The artist as project manager, as producer, is in many ways inseparable from the artist as aesthetic practitioner, as visionary and creator. At all the phases of the projects I describe throughout this thesis, for example, I have been directly involved in the creative process. As art director, my responsibility includes directing aesthetic and technical treatments of the scientific visualization scenes for each project. As co-producer, I oversee the creation, production design, color, and cinematic treatment of the scientific visualization scenes and other project scenes. These components are imbedded in the creative product. On many research projects, I also provide hands-on, digital manipulation of production parameters such as the creation of color transfer functions or compositing elements. Together with my team, I collaboratively brainstorm with external collaborators to provide input for and critiques of the script, storyboards, scenes, and evaluations.

Creating scientific visualizations from computational science presents many additional challenges that transcend the traditional entertainment arts. Computational simulations must align within a scientific narrative as it is being developed for a show. Scientific visualizations are designed and rendered from large-data, supercomputer simulations using some of the most advanced technologies available while retaining the highest quality standards for aesthetic and cinematic treatment in order to provide production quality necessary for general audiences. We confront the truth and beauty paradox in our everyday operations.

Scientific researchers—such as those at the Electronic Visualization Laboratory (EVL) at the University of Illinois at Chicago--particularly value artists for the presentation skills they bring to collaborative projects. Scientists focus on peer-reviewed scientific or

technical journal publications as a primary venue for communicating work and building reputation for earned expertise. In the art world, artists gain experience and rewards from large exhibitions; they hone skills to manage the complexity involved with them (Sandin et al., 2006). The research artist, too, gravitates toward public outreach, exhibitions, and art journal publications. Artists exploring technology choose to publicly demonstrate their emergent technological inquiry in such venues as SIGGRAPH Emerging Technologies or other high-technology conference exhibitions, but also in public spaces: museums, planetariums, television shows, and film. As a result, artistic collaborations with scientists are so valued and mutually beneficial that they often remain stable, spanning many years. EVL has spawned artist/scientist collaborations for thirty-three years, and I myself have worked with some scientists for over twenty (Cox, 1986).

Artists can also collaboratively bond with digital technologies. These may be viewed along a continuum: as merely elaborate tools for expressing a creative vision or, given their "intelligence," a responsive, albeit submissive, partner in the creative process— an apprentice who never attains mastery, but with some training, provides savings in basic labor, and, not to carry the analogy too far, assists with the transportation and physical display of the master artist's creation. The visualization pipeline is an iterative process: a human-computer feedback loop. The visualization expert or scientific user of visualization tools generally preprocesses data; attaches data to modeling schema; and renders data for insight, decision making, and communication. This process enables the expert or user to explore different aspects of the data and refine its visualization. Interactive, real-time software applications provide for the iterative interrogation of data sets (Douglas et al., 2003). Time evolution is a dimension of many data sets; thus visualizations can also take the form of animated sequences of images. However, computational constraints; high-resolution, advanced 3D-CGI rendering techniques; and multiple-terabyte data sets often

68

require batch-mode rendering for animations. Various visualization applications and environments are being developed to address these issues.

Mapping Numbers into Pictures

For data visualization artists, the most important question when beginning a project is typically this: "How can the numbers and loosely correlated facts be designed and transformed into a visual model that makes sense to viewers?" Data mapping is the essential binding of symbolic input to a visual graphic according to some conventional transformation technique. Each scientific discipline either has its own set of established conventions or, if a "young" science, is evolving them. Well-established astronomy practice uses the convention of star catalogues, while young neuroscience is developing the new method of brain atlases. Each scientific community develops consistent, descriptive visualization languages to support its conventions, with coherency and predictability for viewers being primary goals.

Data-driven scientific visualization also has a visual language expressed through conventions. Traditionally, it has been based upon the science of visualization; i.e., the analysis of human visual and perceptual systems. For adherents, this approach promises to yield computer-rendered data visualizations that will enable people to better understand more visual information or make informed expert decisions. The field is a developing system of guidelines and principles, based upon analytical and calibration methods that include what colors to use, how shape-forms present information, and what affects human perception of visual information (Beck, 1966; Ware and Beatty, 1988; Duncan and Humphreys, 1989; Gershon, 1994; Healey, 1996; Ware, 2000, 2008; Rogowitz and Kalvin, 2001).

69

However, as I argued in the first chapter, my view is that visualization is more than perception science and data transformations; it also involves a critical process of interpretation and signification. Experience, habits, cultural contingencies, and discipline-specific preferences affect how people see, use, and interpret pictures (Berlin and Kay, 1969; Berger, 1977; Rosch and Lloyd, 1978; Lakoff and Johnson, 1980; Gregory, 1990; Varela, Thompson, and Rosch, 1991; Stafford, 1999; Brown, 2003). Choice in the representation and mapping of data affects the interpretation as well as final quality of the visualization. For example, glyphs are iconic representations derived from data (Ellson and Cox, 1988). The visualization artist has a range of freedom within which to construct and design these abstract glyphs. These choices correlate to the data sources used and techniques employed to convert numbers to visual CGI models, a process I will describe below, but they also rely on archetypal visual associations that circulate within culture (such as using arrow forms to indicate directed motion or flow).

Data Sources, Transformations, and Techniques

In general, the two primary sources of scientific numerical data are observational and computational. Observational sources include instruments (e.g. telescopes, CAT) and collected or acquired data such as census statistics or textual descriptions. Modeled computational data result from digital scientific and mathematical models that solve physical equations using approximation methods (Wilhelmson, 1988; Kaufmann and Smarr, 1993). The concept of "raw" data is misleading, because it suggests a clean, pure immediacy of the numbers. All computational science data used as a foundation for creating scientific visualizations are mediated and filtered through digital transformation or compression techniques, because most of these scientific data sets are extremely large and

70

complex—up to multiple terabytes across multiple dimensions—making one-to-one visual

mapping to digital screen space impossible. Scientists and scientific visualization artists

are all keenly aware of how this mediation and filtering of data informs design choices,

from computational mathematical models to data-gathering instruments and sensors to the

visualizations of the data derived from them. Here, I present a basic set of these techniques

to demonstrate this process of transforming and filtering data for data-driven, CGI

visualizations. My team has adapted standard approaches. Our most recent research

represents incremental improvements and attempts to address the data challenges

recognized in the field today (Munzner et al., 2006).

The formats and structures across observed and computed numerical data are

diverse, presenting one of the greatest challenges to visualization (Norman et al., 1999;

Reed et al., 2005). Many visualization systems accommodate a variety of data readers and

conversion algorithms (Schroeder et al., 1992; Fruhauf et al., 1994; SCIrun, 2001). Efforts

to design common data formats, standards, and metadata tagging have been successful

(Rew, 1990; Kapadia and Yeager, 1999; Folk et al., 2001; Yeh et al., 2001; SRB, 2003).

Visualization methods can employ higher-level, contextual data attributes to organize and

specify data objects and enable scientific interchange (Hibbard, Dyer, and Paul, 1992;

Rogowitz and Treinish, 1993; Rajasekar et al., 2003). This attention to data classification

is productive; it fosters a wider variety of data flow visualization applications, discovery

environments, and grid applications (Reed, 2003).

Although standards need to be adopted within and across disciplines, the variety of

cross-disciplinary scientific data structures continues to necessitate customized

preprocessing in the visualization pipeline. Visualization employs a number of data types,

or means of organizing basic data, including scalar arrays, vectors, meshes, volumes,

dimensions, and positions. Dimensional data, for example, may be comprised of any
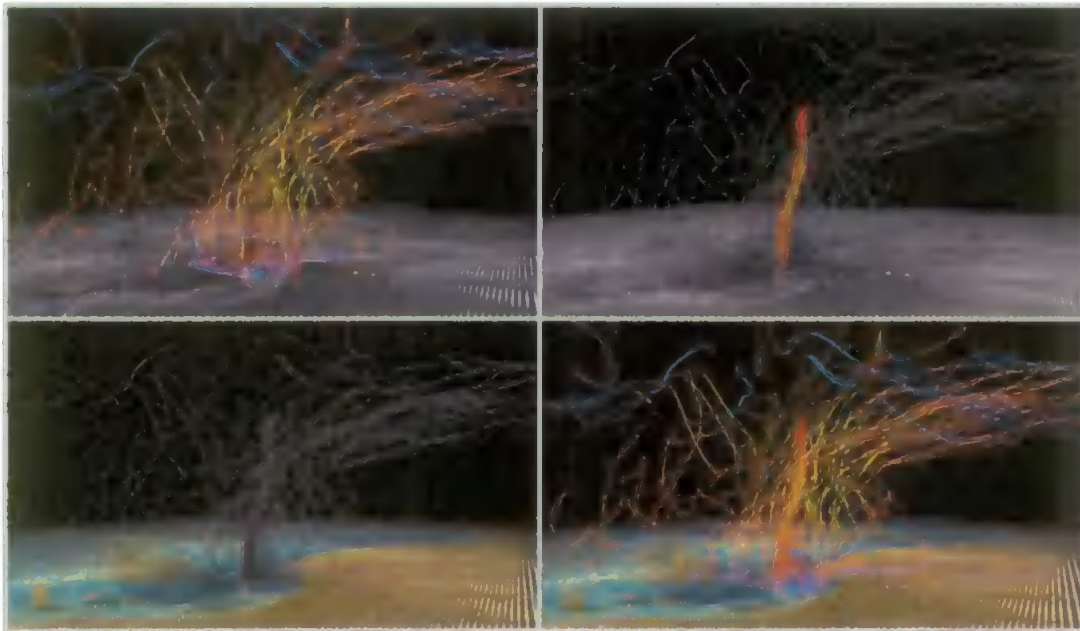
Figure 4. Scientific visualization of a tornado using colored glyphs to distinguish features of interest. In left upper quadrant: colored trajectory glyphs (or stream tubes) show the geometry of air flow. In right upper quadrant: colored spheres locate the central tornado; In left lower quadrant: colored surface cones show variables on the ground; Lower right quadrant all colored glyphs components combined.

number of independent variables. To render a visualization in three dimensions, such as 3D volumes from MRI (magnetic resonance imaging), the number of dimensional variables is reduced to three, along the x, y, and z axes.

Position, an independent variable, is another example, but one that also demonstrates how more complex data is constructed from such basic information. Position points serve as sampling sites for dependent variables, where scalar fields such as density and temperature are measured throughout three dimensions of space or matter. Often, such
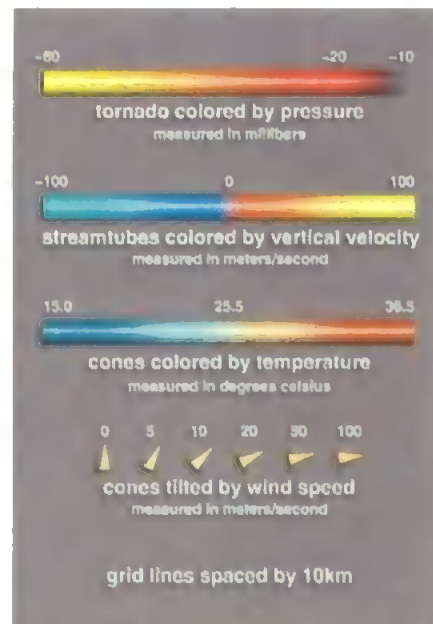
Figure 5. Color legend to show numerical ranges of variables of the tornado simulation. Tornado glyph spheres are colored by pressure; stream tubes by vertical velocity (up is red-yellow, down is cyan-blue); the ground plane cones are colored by temperature. Cones' tilt indicates wind speed.

72

independent variables map to world coordinate systems, such as in the case of geosciences data. However, it is also possible to associate data with glyph attributes such as points, lines, and spheres that cannot be projected within a world coordinate system, such as in the visualization of plastic injection molding (Ellson and Cox, 1988). Glyphs are generally constructed from derived data and have been used to represent very difficult concepts associated with data. Consequently, finite element simulations are often structured (i.e., shaped) according to the geometry of the material being simulated. Associated tensor information may be represented as glyphs on that shape (Haber and McNabb, 1990).

Within the fields of computational science and scientific visualization, grids serve as another complex organization of basic data. They are structured, but they can be regular
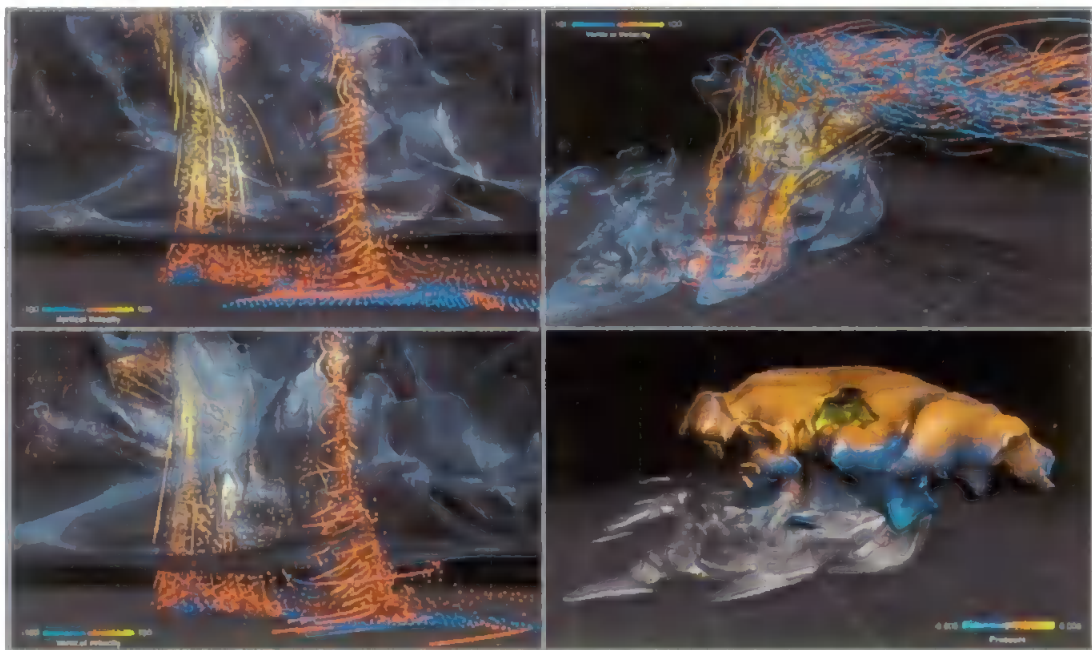
Figure 6. Scientific visualization of supercell tornadic thunderstorm using color and glyphs to indicate microphysical variables: Two left quadrants (upper and lower) show a supercell tornado forming and strengthening when two rotating updrafts begin to merge after 7100 time steps. A sheet of spherical glyph particles was released from the ground plane to trace the air motion upward. The trajectory glyphs trace the paths of spherical particles as they concentrate to form a tornado. The trajectory and spherical glyphs are colored by vertical velocity. When air rises, they are red-yellow; when air descends with negative velocity, the glyphs turn cyan-blue. The right upper quadrant glyph tubes trace air flow during a range of 5600-7200 time steps. The right lower quadrant uses color to indicate pressure in the supercell atmosphere. This blue-orange surface indicates variables of rain, snow, and graupel. The interior hole in the atmospheric surface shows the highest pressure (yellow) where the tornado is beginning to form. All four quadrants show gray, transparent surfaces where cloud droplets and ice crystals can form during a supercell.

73

grids or irregular. For example, (Figure 1, 4, and 6) are visualizations of a 3D-structured

volume of atmospheric computational data (see Practicum Compilation DVD, 1: General

Visaphor Sequences, Tornado Chaser 1.2.1). The primary volume data set is an irregular,

3D grid with seven microphysical dependent variables associated with each 3D-grid cell.
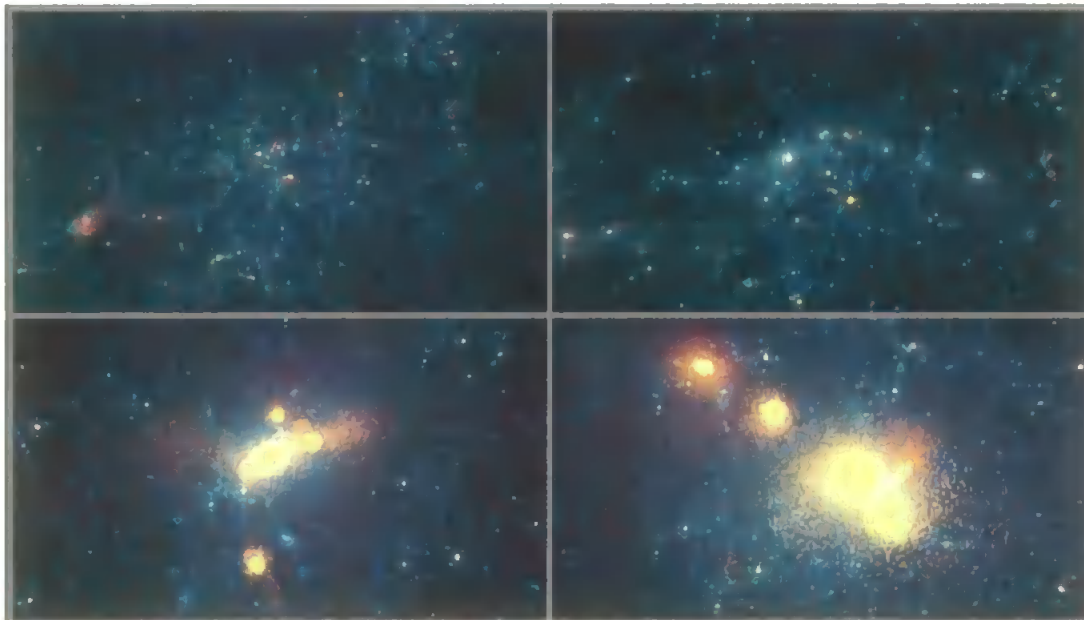
Figure 7. Evolution of the early universe, *Runaway Universe* version: This sequence of images shows large-scale to small-scale structure of the universe evolving. Four frames visualize a scientific AMR simulation that used 200,000 Computational Processing Units (CPU) hours on Silicon Graphics Origin 2000 to resolve the formation of individual galaxies as well as their webs-like large-scale distribution in space. Color is used to differentiate gas density, dark matter, birthing stars and other small-scale features. One continuous camera moves from 300 million light years of the cosmic web formation in the left upper quadrant down to a scale of 30 thousand light years of interacting protogalaxies and star formation shown in right lower quadrant.

In constrast, Figure 7 shows a simulation of the evolution of the universe using

Adaptive Mesh Refinement (AMR). AMR numerical-simulation techniques for

computational fluid dynamics (CFD) employ a structured rectilinear grid, but locally adapt

producing sets of nested grid cells that have finer spatial and temporal resolutions. Figure

7 is an example of the time evolution of an AMR cosmological simulation, in which the

temporal and spatial domain varies many orders of magnitude, from a large-scale, cosmic

web of dark matter to small-scale features of star formation and protogalaxies (Ferris,

74

1982; Geller and Huchra, 1989; Norman et al., 1999; Cox, 2000, 2003). Upper-left and upper-right of (Figure 7) show a large-scale structure refining to form a filamentary web of gas and stars.

Lower-left and lower-right of (Figure 7) are later frames in the same simulation that show birthing stars and protogalaxy interaction as the camera zooms in to view these fine-scale features of the simulation (see Practicum Compilation DVD, 1: General Visaphor Sequences, Evolution of the Universe, 1.6.1). The AMR numerical technique yields a 3D data structure that is locally unstructured but employs the simplicity of a rectilinear grid (Berger and Oliger, 1984; Weber et al., 2001). Local adaptive refinement on a rectilinear 3D grid produces a greater level of complexity and computational efficiency.

In contrast, scattered data such as those found in text information (Schumaker, 1976; Rosenblum et al., 1994) and bioinformatics are not structured; they cannot be mapped to a Cartesian or 3D rectilinear grid. (Figures 2 and 3) are a visualization of unstructured data sets yielding probability matrices and relational phylogenetic trees; these data are not ordered according to 3D spatial position. Although most sensor-equipped instrumentation, such as MRI, produces structured data sets that are regular, dense, and 3D--with attributes associated at each point in the volume--some instrumental data can also be unstructured, scattered data, such as in the form of sparse data samples from roving oceanic ships equipped with sensors.

Whether data is structured or scattered / unstructured, there is almost always too much data to be displayed on the screen. Reducing visual clutter is an important part of the computational scientific visualization process and means directly making choices about what data should be shown and, from an artistic perspective, how.

Reducing Visual Clutter: Progressive Disclosure

Since the enormous data sets common to science preclude a visual, one-to-one

mapping to digital screen space, visualization techniques for reducing dimensions have

been developed. Discrete values from an n-dimensional data domain are mapped onto

pixel colors. Figure 4 exemplifies how color can be used to map distinct components of a

tornado simulation. Figure 5 shows the color legend that corresponds to the color-mapped

components. Imagine here, for example, that an artist maps three numbers from scientific

data to three corresponding colors he / she has chosen:

1, 2, 3 → red, green, blue

However, even after the large, base data set has been significantly compressed with such

standard techniques, the problem remains that on-screen graphics appear too cluttered,

noisy, and incomprehensible. As a result, sophisticated techniques have been designed to

efficiently "cull" occluded CGI elements (Durand et al., 2000). Progressive disclosure is

an important method for reducing visual clutter and enabling the continuous, in-depth

exploration of the data set. Progressive disclosure is an overall approach that enables the

interactive remapping of data, viewing data from arbitrary angles, and revealing data sets

at various resolutions and levels of detail.

Progressive disclosure employs filtering techniques such as feature and data

extraction, polygon reduction, multi-resolution models, scaling, and feature visualization.

Sub-sampling continuous or very large, discrete data sets is necessary for most

visualization in order to provide a global view that remains an accurate approximation.

Regular- or irregular-interval sub-sampling can reduce the underlying 3D data field,

visually capture the continuous function of the data (Jiang et al., 2001; Shaffer and

Garland, 2001), and demonstrate efficiency through providing a fast overview. However,

sub-sampling errors and interpolation techniques can lead to misleading artifacts (Carr et

al., 2001). Multi-resolution modeling, polygon reduction, and feature simplification enable

access to levels of detail and enhance interactivity in the visualization pipeline (Walter and

Healey, 2001). Advanced, multi-resolution modeling for high-resolution, irregular grids

provides a method for zooming into spatially subdivided regions of interest, to represent

them at higher resolutions and finer scales (Gross, 1994; Kobbelt et al., 1998).

Progressively disclosing the level of detail enables a smooth transition from coarser to

finer representations and manages data complexity.

Many progressive disclosure techniques depend upon interactive, disk data

retrieval. Novel data representation schemes and adaptive techniques have been developed

to increase efficiency and allow access to structures in an increasing order of smoothness

(Machiraju et al., 1998). Techniques have also evolved for representing multi-resolution

volumetric data for interactive and realtime techniques. Data compression using discrete

cosine transformations for volumetric scalar data can decrease rendering time by a

significant factor and enable more efficient geometric computations (Gross, 1994; Shaffer

and Garland, 2001). Likewise, hardware rendering techniques provide increased efficiency

for interactive and batch-mode volume rendering; this research is fueled by technological

advances (Westermann and Ertl, 1998; Chen et al., 2008).

I turn now to focus in more detail on a particularly useful method of progressive

disclosure, feature extraction. Multidimensional data and unstructured data often require

feature extraction to reveal complicated, embedded processes. Feature extraction is a form

of interactive filtering in which a "feature" is defined as anything that is interesting in the

data (another editorial decision). The practice is based on the assumption that not all data

77

needs to be represented directly; derived data relationships, attributes, or variables can provide what information is deemed important (Van Walsum et al., 1996; Hubeli and Gross, 2001).

Glyphs are commonly now used to show features of the data. Glyphs are symbolic / iconic, graphical objects that are "bound" to data with attributes such as shape, color, size, position, and orientation. They have evolved in 3D computer graphics as part of the literal, visual language of visualization. Most people understand glyphs in terms of a literal translation of the data; however, as with geographic maps, they once had novel origins. A Kodak research scientist and I developed one of the first 3D CGI glyphs (of plastics) in 1988 (Ellson and Cox, 1988; Keller and Keller, 1993). Glyphs have since become an especially important scientific visualization technique that artists use to represent complex data, as well as an essential part of many visualization environments (Ellson and Cox, 1988; Haber and McNabb, 1990; Foley and Ribarsky, 1994; Ware, 2000, 2008).

At AVL, we employed glyphs in creating our visualization of the tornado for *Hunt for Supertwister*. The other visualization artists in my team and I began our dynamic rendering through engaging in an iterative work process with scientists, making editorial (i.e., mathematical and graphical) and aesthetic alterations to the data set and its modeling. Figures 4-6 illustrate the glyphs we used to express the turbulent and complicated airflow in an atmospheric simulation of a tornado. These simulations are "idealized" models. The original, large-scale data set in Figure 6 is a three-dimensional (3D) cubic volume of gridded cells (418 x 418 x 80). Each of these 14-million cells has seven associated, dependent variables of microphysical data, such as ice and rain.

1. volume of data (98-million numbers) → visual model

2. subset of the data → glyph

78

A typical method for rendering complicated flows in process--where salient features may be hidden by turbulent clutter--is to release particles within the flow field and trace the arrangements of the particles. Imagine that clusters of leaves are released into a dust devil in your yard; these imaginary leaves have no friction or weight. They simply follow the airflow and trace the pattern of the invisible wind. Visualizing tracer particles as glyphs helps the artist to correlate flow features within the associated microphysical data in a clear, easily understood way. The colored, spherical balls and stream tubes in Figure 6 are glyphs that are used to represent flow in the temporal evolution of a severe thunderstorm. The spherical glyphs function like tracer particles to indicate the positions of air currents within the flow. The stream tubes provide a history of the flow. On the left quadrants of Figure 6, the stream tubes trace a short "history" in the life of individual particles during the time of the simulation. In contrast, in the right upper quadrant of Figure 6, stream tubes trace a long "history" of tracer particles, providing a more complete view of flow geometry. In Figure 6, the stream tubes and spheres have been colored by color scales in each quadrant to indicate when they are flowing upward (positive vertical velocity) and downward (negative vertical velocity).

Figure 4 shows another example of feature extraction performed through computing and coloring derivative particle data from another 3D structured data set of a simulation that produces a tornado. Again, visualizing the tracer particles as glyphs clarifies and helps correlate and distinguish features within data-field quantities. The data glyphs represent are partial and selective; they are derived through mathematical approximation methods, which involve sampling choices and the testing of various thresholds. These methods are expressed through operative rules called algorithms. In Figures 4-6, the derivative particle trajectories are computed by integrating the velocity

79

field using a fourth-order Runge-Kutta algorithm (Davis and Rabinowitz, 1984). Velocities between grid cells are tri-linearly interpolated and registered with other dependent variables. As discussed earlier, Figure 4 shows vertical velocity values mapped by color onto glyph stream tubes. Pressure values are mapped onto the spherical balls that locate the central tornadic rotation. The ground plane shows cone glyphs that indicate wind speed and direction by the tilt of the cones. The ground plane is colored by temperature. Figure 5 shows color legend details. These glyphs represent extracted features from the primary, volume structured data set. Features are emphasized in each of the four quadrants through color. Like Figure 6, the derivative particle trajectories in Figure 4, have been computed by integration. Velocities between grid cells are interpolated and registered with other dependent variables. This approximation algorithm calculates the trajectories of the vertical velocity showing updrafts and downdrafts of air.

flow of air traced in space-time → glyph position-orientation

color values of up-down or pressure → glyph local surface

In Figure 6, iso-surface thresholds are derived from the 3D-grid data using a Marching Cubes algorithm (Lorensen and Cline, 1987), which is an approximation method for extracting surfaces from a volume. The grey transparent films in all quadrants of Figure 6 show a selected numeric threshold to show cloud droplet and ice crystal formation. The right lower quadrant of Figure 6 also shows colored iso-surfaces colored by pressure values. That is to say that at each point on the iso-surface, a color scale shown in the quadrant is mapped to the iso-surface to indicate a pressure value scale. The blue-orange iso-surface indicates variables of rain, snow, and graupel. The interior hole in the

80

atmospheric surface shows the highest pressure (yellow) where the tornado is beginning to form.

boundary of microphysical variables → iso-surface thresholds

pressure values → color on the iso-surfaces

In progressive disclosure processing, decoupling computer-intensive techniques is often more efficient than processing them together. Extracting features--such in the case above with releasing particle trajectories through large, time-varying flow fields--can be time-consuming due to calculation and disk input/output requirements. With sufficient processing and memory, users can interactively place probes in data, release particles, and visualize the results. Decoupling the particle-advection calculation to run on a fast parallel machine with quick access to large data sets enables efficient, interactive exploration of particle trajectory visualizations. Recently, we have seen a blending between observational CGI techniques and computer graphics rendering. However, most of this research is for experts and scientific analysis (Li, Fu, and Hanson, 2008).

We have created a variety of tools, software, and utilities to handle the visualization issues described above. Figure 8 indicates some of the new tools we developed for the *Hunt for the Supertwister* and *The Black Holes Project* to design, color, cull, choreograph, and render multiple terabytes of computational data into a variety of output formats. In Figure 8, left upper and lower quadrants show tools for coloring tornado and AMR data,

81
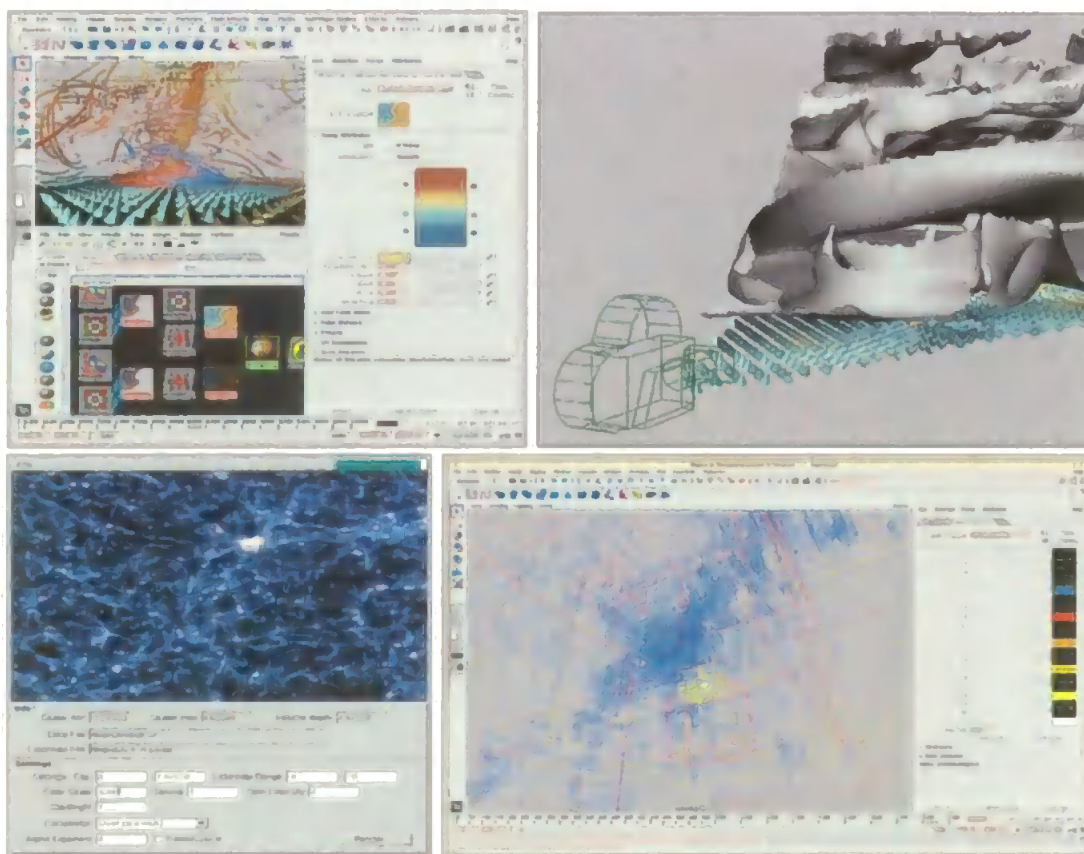
Figure 8. The NCSA AVL has created many utilities, plugins and stand-alone software applications to create, process, choreograph, and render data into scientific visualizations. Upper left and right show customized plugins that enable Maya software to handle data. This customized plugin enables an artist to design, color, and cull data for rendering of tornado scientific visualization. Lower left quadrant shows in-house software to color AMR data. Right lower quadrant shows customized Maya plugin to help explore, design, and choreograph multiple nested grids of AMR data.

respectively. The right upper quadrant of Figure 8 demonstrates camera culling using Maya software to exclude objects not in the camera view. The lower right shows nested AMR boxes within Maya software and the plugin to preview and choreograph nested, irregular AMR data.

My NCSA visualization team and I have developed a collaborative methodology and a visualization pipeline (Figure 9). This pipeline is organized into four primary areas: data management, graphical data creation, visualization processing, and rendering. We
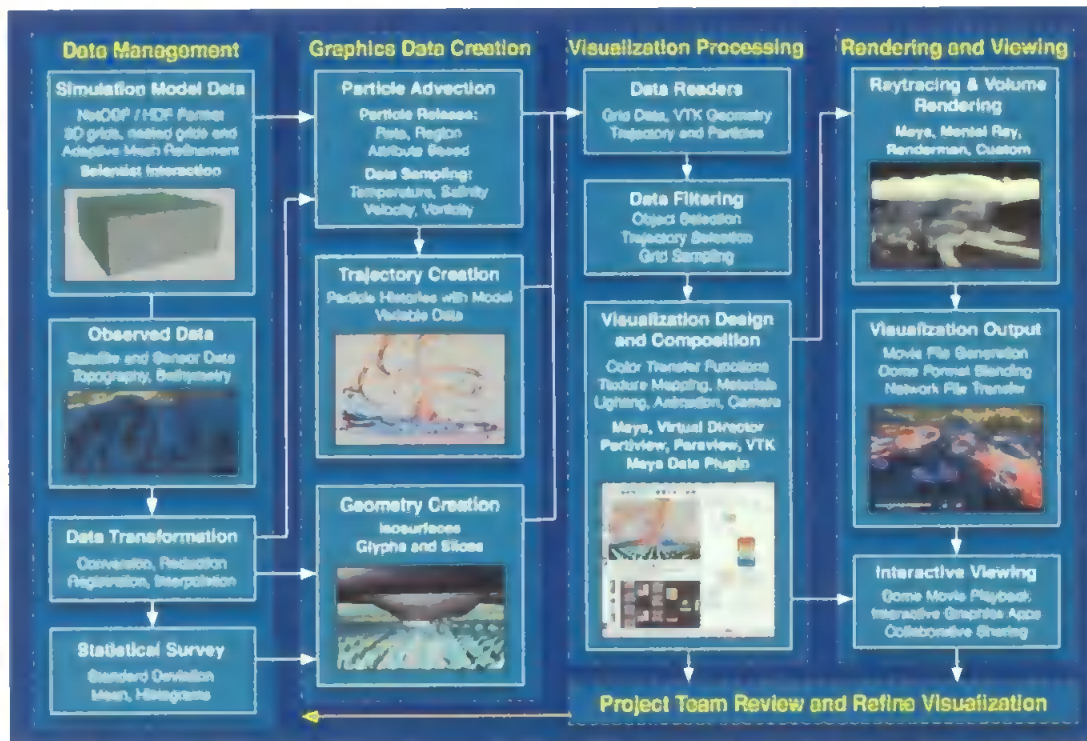
Figure 9. NCSA AVL visualization pipeline involves four main thrusts where team members collaborate and iterate to create visualization renders for review and refinement. 1) Data management of large-scale computational data; 2) graphical data creation including glyphs; 3) visualization processing including composition, color, choreography, and design of scenes; and 4) interactive viewing, rendering management, and formatting for final output to a variety of formats ranging from small-scale desktop Quicktime movies to large-scale dome-master, IMAX resolution renders, or high-definition stereo.

have developed a variety of interactive and batch software for processing data, filtering data, generating derivative data such as trajectories, employing a variety of renderers, and managing series of animations for visualizing multiple terabytes of simulation data. We work together in a collaborative, iterative process to create visaphors. I orchestrate this overall process, direct group strategies, and provide input throughout the process. I focus on design, refinement, and review. Often a single visaphor such as the tornado will take as long as one year to complete final renders for inclusion within a large-scale production.

As this discussion has suggested, sophisticated mathematical and computational approaches dominate CGI research; these have proven extremely useful. However, almost all of the numerical approaches mentioned above involve the editing and filtering of data that provides the foundation of the visual model, creating a derivative, or tertiary,

83

relationship to the original data. When we developed the above AMR evolution of the universe visaphor, for example, we used data from a scientific numerical model that incorporated the known physics of a closed system: a simulation developed by scientists to describe and compute astrophysical objects in the early universe. Much of the research that provides the basis for astrophysics calculations are based on evolving computational algorithms relating to nuclear research that began during World War II. John Von Neumann and Herbert Weiner developed much of the mathematics used to describe nuclear reactions and to symbolize and calculate them inside of nineteenth-century computers. The extension of this work in simulation has led to calculations that today provide solutions to equations that describe the evolution of the universe, such as what is likely to have been the nature of the first star or evolution of the universe (see Practicum Compilation DVD, 1: General Visaphor Sequences, Star-Galaxy Formation, 1.3 and Evolution of Universe 1.6). The resulting visaphor provides yet another transformation of this data, one that adds as much of a hermeneutic layer as did its original simulation. However, despite the aesthetic and hermeneutic nature of visualizations, professional conferences tend not to focus on considering them as such (Chen et al., 2008).

Camera Considerations

After visaphors are designed and created, visualization artists choreograph camera movement around and through them. In doing so, we must consider the shape and dimensions of the viewing surfaces onto which they will be projected. For example, the visaphor scenes for a digital-dome show like *Black Holes* are much longer in screen-time length, and the camera is choreographed to move slowly and majestically, when compared to the relatively short time-length edits used in the *Monster of the Milky Way* PBS NOVA

show (compare in Practicum Compilation DVD, 4: *Black Holes: The Other Side of Infinity* digital-dome excerpts with *5: Monster of the Milky Way* PBS Show excerpts). Why is this so? The digital dome encloses the entire visual field within a moving image. As a result, audiences cannot easily tolerate fast visual motion of the camera viewpoint, as our own experience working and designing choreographies inside the CAVE™ and Hayden's digital dome have demonstrated. Too much motion creates simulator sickness, a dizzying condition of disorientation often experienced in virtual reality, similar to motion sickness during actual physical movement in a vehicle (Zyda et al., 1997; Sherman and Craig, 2003). Then, too, audiences may prefer grander visual gestures in the immersive digital dome since its visual language tends to be understood in terms of large-venue cinematic arts (Berton, 1990; Wright, 1990; Yu et al., 2007). In contrast, the rectangular television screen on which most PBS NOVA viewers watch *Monster of the Milky Way* does not enclose the visual field unless the viewer is only inches from the screen. As display systems advance, home television screens will get larger and may someday be stereo. More now than ever before tend to be HD-enabled. However, we have learned that television audiences prefer faster edits, shorter shots, and swift movement in that delivery format, which is likewise more typical of small-scale cinematic arts.

Repurposing Visaphors for Other Projects

When intellectual property considerations allow, visualization artists often reuse scenes they have created for one project in a concurrent or later project. The repurposing of existing visaphors and their camera work may include revisiting the visaphor's rendering to produce alternate renders with changed elements, from colors to glyphs to dynamics. Camera choreography, scene length, visual scale, and other features may

change as well. For example, my AVL team and I developed a data-informed, simulation-augmented model of the Milky Way in collaboration with scientists for *Runaway Universe*. We decided to repurpose the scene in which the model appeared for *The Black Holes Project*. However, into the new scene dynamics for our highly detailed flight into the center of the Milky Way, we needed to integrate Dr. Andrew Hamilton's Black Hole Flight Simulator (BHFS) application output (see Practicum Compilation DVD, 4: *Black Holes: the Other Side of Infinity*, Sequence 9 b and *5: Monster of the Milky Way* Scene 1 Sequence 3). The BHFS is a sophisticated ray-tracer simulation that solves Einstein's equations to create a "lensing" effect of a black hole over a background (known as the Hamilton Lens Effect). In collaboration, we visually integrated the virtual flight through the Milky Way with BHFS digital-image output through scene design, choreography, and color. We collaborated to transition from the Milky Way to the BHFS "lensing" effect in developing several shots. This collaboration was challenging. Yet, it was well worth the care: this scene provided the climactic ending of the planetarium show (see Practicum Compilation DVD, 4: *Black Holes: The Other Side of Infinity*, Sequence 9 b).

Designing Visaphors for Popular Audiences: A Case for Digital Domes

Up to this point, my discussion of design considerations in transforming and presenting data has often assumed that the end audience for the visualizations produced would be made up of experts. Such experts are already trained to understand conventional, scientific visualizations and to interpret the data on which they are based. Public outreach gives data-viz artists additional considerations, for the data presents a whole, new level of abstraction, its own multilayered, metaphorical reality. Information visualization and immersive environments for museum audiences are emerging areas of research that are

gradually gaining more attention in terms of audience differences (Hinrichs, Schmidt, and

Carpendale, 2008). Understanding visaphors requires that audiences interact imaginatively

not only with its creator (or Renaissance Team of creators), but also with his or her

discourse community and its most basic assumptions. Certainly, science educators might

be encouraged to incorporate visaphoric literacy into their curricula for students beginning

at very early ages. Media education is crucial in our information age.

Data-viz artists may also assist untrained, general audiences, those who are not

readily familiar with the scientific presentation of ideas, in understanding visaphors

through grounding them in everyday spatial and temporal experiences. For example, I

believe that the NSF Net visaphor[3] (in this case, a static image) I created has been so

successful--having been reproduced continually over the past 15 years for public

consumption--because of its grounding in a spatial map of the United States. This familiar

ground helps the invisible national network of internet connectivity and hubs seem less

abstract (Figure 10).

Books such as *Atlas of Cyberspaces* by Martin Dodge and Rob Kitchin (2001)

illustrate the need for, and begin to provide an education in, reading visaphors. Digital-

dome environments also provide a special opportunity for reaching a broader public, to

enable them to experience scientific visualization and to teach them about computational

science, its importance in contemporary science, and the role visualization plays within it.

As part of this effort, the one-hour NOVA special *Runaway Universe*, which aired in HD

format on PBS in November 2000 and again in July 2001, tells the story of how scientists

---

[3] See, for example, the following sites, where the image appears in a variety of contexts:
http://www.visualcomplexity.com/vc/project_details.cfm?index=17&id=17&domain=; http://www.livinginternet.com/doc/merit.edu/mapcredit.html;
http://www.nsf.gov/news/news_images.jsp?cntn_id=110776&org=NSF;
http://www.mappingcyberspace.com/gallery/colourplate1d.html
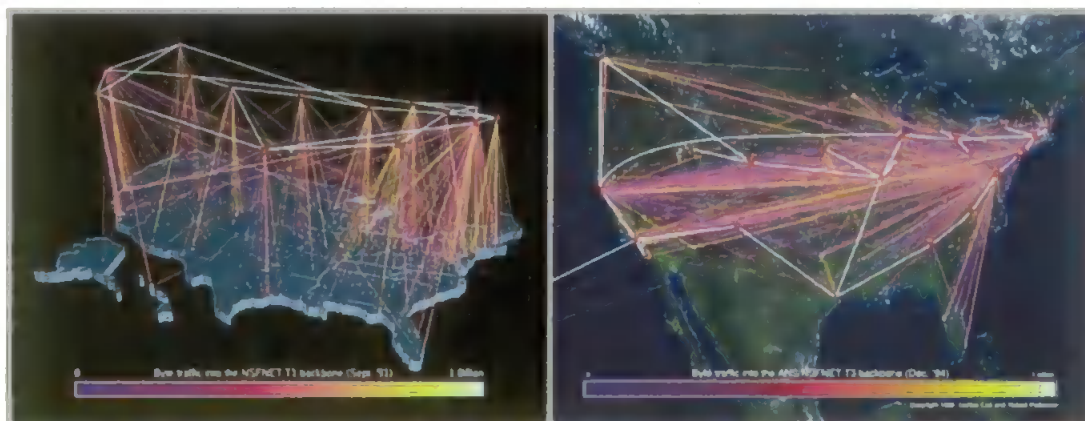
Figure 10. The NSF NET visualization: the first data-driven visualization of the first academic internet. Above-left shows the NSF NET backbone in white and its connections to client networks. The client networks are colored by traffic level into the backbone for the month of September 1991. Right, the map shows traffic into the NSF NET backbone for the month of December 1994, the last heavy usage month prior to privatization. Created by Donna Cox and Robert Patterson, 1992 and 1996.

map the universe and require visualizations to make sense of their data. Bob Patterson, Stuart Levy, and I visualized astronomical data for the program. Our visaphors take viewers on a virtual voyage from the early universe (see Practicum Compilation DVD, 1: General Visaphor Sequences, Evolution of the Universe, *Runaway Universe* 1.6.1) to the formation of our galaxy, then out of the Milky Way to the Virgo cluster of galaxies (see Practicum Compilation DVD, 1: General Visaphor Sequences, Milky Way Virtual Flights, *Runaway Universe*, 1.5.1). Here, we repackage these visaphors with narration and present the relationship between the visaphoric computer graphics images that the public experience and the telescopic star catalogue-based and supercomputer simulations that inform them. Since my work focuses on such public education and appeal, I turn now to the importance of digital-dome technologies to my scientific visualization practice.

Immersive, High-Resolution Environments

Visaphors can be displayed on a variety of media display devices; many of the visaphors developed for one are re-used for another. However, display media, their

88

location, and the cultural associations with that location can provide important communication contexts for visaphors that influence audiences. Planetariums seem a "natural" cultural fit for the science-education media that incorporate our scientific visualizations. They evoke the oxymoron of a sacred secular space, with their technically enhanced dome opening onto projected or virtual heavens. From the Etruscans' first architectural domes in 500 B.C.E. (Lehmann, 1945) to our state-of-the-art, contemporary, immersive, digital, full-dome theatres, people have been enthralled with the inspirational power, architectural beauty, and visual adornments associated with domes. In his review of dome environments, David McConville sees domes as a profound expression of the sacred that crosses cultures; we can only suppose because of their association with the sky and, so, the heavens: "From Buddhist stupas to Islamic mosques to Christian cathedrals, these structures have been used as places of ritual, indoctrination, and transcendence" (2007, p. 69). Buckminster Fuller developed dome technology as a way of using art and science to "extend and expand upon experience"(Snyder and Vesna, 1998, p. 290). In modern times, cinema and dome architecture have collaborated periodically to provide the public with stimulating experiences in both art and science (Mitman, 1993; Robertson, 2002; Tracy, 2007; Yu et al., 2007).

In addition to sacred associations, planetariums evoke both a classroom and a cinema--where audiences expect to be edified as well as entertained—but on a more spectacular scale, with greater sensation and potential for emotional response. The relationship between cinema and popular scientific outreach is not new. Before the early twentieth-century growth of domes around the world, we find a long history of the tie between science demonstrations and public outreach in the form of expositions such as the World's Columbian Exposition held in Chicago, Illinois in 1893. The historical

89

connection between these types of grand, public science demonstrations and early cinema is well described by Michael Punt (2000).

Historically, one of the most successful astronomical dome projection systems was the Zeiss optical star projection system, which was developed by the founder of the Carl Zeiss Optical Co. in 1846. The Zeiss system was employed by the Adler Planetarium in Chicago, the oldest in the western hemisphere, as early as 1930. Many planetariums followed suit during the 1930s, including the Hayden planetarium in 1935. Although popular, the Zeiss projection system, often called a "star ball," had its limitations. It only projected astronomical content, such as stars and constellations.

Digital-dome projection environments at planetariums are the most recent vehicle developed to provide large audiences with an educational science spectacle. They combine the architectural surround of a dome with the digital cinematic qualities of CGI imagery. In the contemporary digital dome, however, there is an important connection between the full-dome spatial/temporal environment and the computer graphics camera that enable audiences to take virtual tours. Digital-dome projections of CGI affect the viewers much like digital cinema and provide the visualizations artists with the powerful cinematic and metaphoric language that has developed through cinema over the years (Whittock, 1990). Due to human peripheral motion vision, the digital camera combined within the dome can create an immersive experience, emulating stereoscopy. In the digital dome, human peripheral motion vision may be affected by the moving spatial content, resulting in an immersive, stereo-like, embodied experience (Arnheim, 1974; Anderson, Drasdo, and Thompson,1995; Walker, 2005).

Museums, in contrast, tend to serve as halls of memory in which Western cultures and those influenced by them to exhibit the (supposed) sum of human civilization, its experiences and knowledge of the social and natural world. Although the movement of

patrons through museums, as they tour chronological exhibits with occasional waypoints of more intense study and interest, is replicated in our cinematic offerings, our dynamic exhibits--whether cinematic or fixed--seem to drop away the closed walls and cases of the museum to bring the encounter to life, enabling greater imaginative participation for audiences. In digital domes, audiences are also given the embodied sensation of taking flight.

Monographic full-dome projection such as ours does have the limitation of not being as fully immersive as the stereoscopic, head-tracked CAVE™ experience. In the CAVE™, the experiencer's head and visual motion are tracked to a high-immersion, 260-

Figure 11. NCSA Passive Stereo Theater - presenting 3D visualizations at conference and art exhibitions

degree field of view, with full head-tracking for each eye. In contrast, low-immersion environments offer no head-tracking or stereoscopy and a more limited field of view. Yet, research has demonstrated that humans can have a very powerful experience in low-immersion environments (Bowman and McMahan, 2007). Specifically, research has shown that people experience increased spatial understanding in low-immersion environments, such as the GeoWall or a high-definition stereodisplay (my Advanced Visualization Laboratory team uses use this type of HD stereo theater at NCSA for demonstrating our work to visitors and conferences) (Figure 11). Although many low-

immersion environments offer a 90-degree field of view, a digital dome may allow as much as 180 degrees. Most importantly, digital-dome projection enables many hundreds of people to share a virtually embodied experience. Figure 12 shows part of the AVL team standing in the Denver Museum of Nature and Science full digital dome. *The Black Holes Project* star orbits in the Milky Way visaphor are displayed as a still image on the digital dome behind the group members (see Practicum Compilation DVD, 4: *Black Holes: The Other Side of Infinity,* Sequence 8).

Such public engagement drives forward our innovations of aesthetic technology. Michael Punt has successfully argued that both early digital and cinema technologies

evolved from the convolutions, conflicts, and careers of individuals in response to their environments, including their publics (2000a). Large-scale audience venues have a particularly powerful impact on

Figure 12. Cox and team in the Denver Museum Dome Theater standing in front of *Black Holes* star orbits on the dome.

aesthetic technology development.

Since the end of the twentieth century, full digital-dome (i.e., domes with non-stereo spherical projection systems) development has proliferated. Much of this development has been in response to audience demand for show flexibility, combined with planetarium-style settings (McConville, 2007; Petersen, 2008). For example, the *Black Holes* digital-dome show demonstrated new ways to integrate live-action into full-dome spherical projection in order to expand content for audiences (Yu et al., 2007). Figure 13 demonstrates how a single dome-master image is created from eleven rectilinear images. We first choreograph and design a high-resolution composition of the visualization using a

92

"wide angle" CGI lens to generate eleven rendered panels; each panel is assigned to a projector location. Then we "blend" the images into a dome-master image using our AVL blender software. Each dome-master requires eleven images to cover the field, and there are thirty dome-master images per second of animation. Therefore, a one-minute DMNS digital-dome movie will require 19,800 images at 1280x1084 pixels each (eleven images per dome-master x 30/second x 60 seconds). Our blender software formats

Figure 13. Dome-master: DMNS digital dome showing 11 projectors that are edge-blended. Eleven images are rendered and blended into a dome-master image that covers the hemisphere of the dome

imagery for various domes, such as Hayden Planetarium's 2000 dome technology with a seven-projector system at 1280x1024 pixels per projector.

Considerable evidence to support Punt's view is also provided by data-driven scientific visualization's history of cross-pollination between supercomputing centers and the entertainment industry, which has resulted in new visualization and CGI techniques. It is not an exaggeration to claim that CGI visualization research into virtual reality for scholarly and educational purposes have developed through their technological synergy with popular cinematic special effects and interactive games (Zyda et al., 1997; Cox, 2000; Francis, et al., 2003; Sherman and Craig, 2003). Although the cinematic capabilities of digital domes are central to my work and its elaboration in this thesis, they ought also to be

valued for their capacity to support important telematic art exhibitions and interactive, remote collaborative capabilities, such as Virtual Director™.

My AVL team and I have focused strategically on the digital-dome technologies for displaying visaphoric art in order to provide this powerful, embodied experience. We have collaborated with three of the top United States planetariums (measured in terms of sophistication of programming and technical specifications) that have rebuilt or redesigned to create digital domes: Hayden in NYC, Gates in Denver, and Morrison in San Francisco. We have also recently worked closely with Adler in Chicago, which is the oldest planetarium in the United States (Stephenson, 2005) and one of the largest and most visited (Neafus, 2008); it has just upgraded its dome technology. Digital-dome technology couples the flexibility and advancements of digital cinema with the spatial and transcendent power of dome immersion for large audience venues and scientific expositions. In the *Black Holes* digital-dome show for Gates Planetarium, for example, we designed and projected live-action integrated with computational science for the first time in planetarium exhibition history.

To illustrate the potential of tele-immersive experiences to reach audiences, and to instance a process by which it can be realized, I next provide a brief account of my work for three high-resolution immersion projects: *Cosmic Voyage*, an IMAX film for which we developed the Virtual Director™ application, in part to support collaboration at a distance; two space shows and a permanent installation for the Hayden Planetarium, for which we consulted on the projection systems; and the *Black Holes* digital-dome show, for which we formally evaluated audience response.

Cosmic Voyage and Virtual Director™

In order to create new aesthetic experiences, supporting technologies must

sometimes be developed. The fifteenth century invention of linear perspective necessarily

required new, mathematically-based techniques on canvas and paper for conveying depth

(from horizon line to vanishing point). Scientific visualization's invention of fluid spatial

dynamics has likewise necessitated new techniques for manifesting such novel

representations. This was the case when, in 1994, I signed on as Associate Director for

Scientific Visualization and Art Director for the PIXAR / NCSA segment of a large-scale

film project, *Cosmic Voyage*, an IMAX science-education movie about the relative scale

of things in the universe that was first shown at the Smithsonian Institute, which helped to

fund its creation. Because computational science and visualization played an important

role in the making of *Cosmic Voyage*, the technical and creative demands we faced were

significant. We employed the advanced technologies of supercomputing and visualization

to artistically render images of galaxies colliding in swirling, paint-like effect, destined for

projection on an IMAX screen. A typical IMAX screen is about 70-feet across, making the

movie more than ten times the film emulsion area of a regular Hollywood 35-millimeter

movie. In our design, we accounted for the fact that IMAX totally surrounds the audience

with image and audio; viewers are immersed in a powerful, if partial, sensory experience,

one that, even more than is the case with conventional cinema, inspires their

consciousnesses to leap from the world of the theater to that shown on the screen and

perhaps even vibrantly beyond its silver surface.

Adding to the project's challenge was our need to collaborate with a global

Renaissance Team of artists, scientists, and technologists to realize an unprecedented

number of data-driven visualizations. We needed a method to collaborate technically and creatively across distances, one that allowed for kinetic, dynamic modes of representation. To answer that need, Robert Patterson; Marcus Thiébaux, then a graduate student at University of Illinois; and I created Virtual Director™, a software framework that operates in the CAVE™, a room-sized, virtual environment with a rear-screen projection system that allows users to see in 3D stereo (Sandin, DeFanti, and Cruz-Niera, 1993, 2001).

Virtual Director™ enables collaboration over the Internet so that users can interact together even though they may be located at great distances from one another. Virtual

Figure 14. Four-way, simultaneous Virtual Director™ collaboration: 1) left upper Infinity Wall,; 2) right upper Immersadesk; 3) left lower CAVE™; and right lower desktop.

Director™ also provides a "choreography" and "navigation" system that enables users to control the virtual camera, record frames, and see the recording on the CAVE™'s virtual television screen (a demonstration is provided on the Practicum Compilation DVD). Virtual Director™ creates a collaboratory space for users. Figure 14 shows a synchronous, four-way, remote virtual collaboration using Virtual Director™. Four collaborators communicate and fly through scientific data and virtual space. They see each other as avatars through high and low resolution immersive and non-immersive displays. Collaborators "see" each other as "smiley face" avatars in their respective screens. Each collaborator has complete control

96

of their own "flight" and orientation in a shared virtual space over scientific visualization data. We have used Virtual Director™ to simultaneously collaborate with scientists at the Stephen Hawking laboratory in Cambridge, UK and scientists at University of California (see Practicum Compilation DVD, 2: Virtual Tools, 2.2). William Wulf defined a "collaboratory" in 1989 as a "center without walls, in which the nation's researchers can perform their research without regard to physical location, interacting with colleagues, accessing instrumentation, sharing data and computational resources, (and) accessing information in digital libraries" (Wulf, 1993, p. vii). Our virtual design provides each user with an independent point of view, enabling the user to navigate independently while creating and sharing camera paths. Users share the visual "space"; they see the same environment, but they can fly to different locations within that space. Using Virtual Director™ software, a user is represented over the network as an avatar and can see other avatars (i.e., other collaborating users) floating and flying in cyberspace.

The experience of using Virtual Director is wondrous, and not only because of the power over environment that such virtual spaces and technological extensions of agency allow. People understand new technology by appropriating understandings from other concept networks, and in virtual reality environment-cyberculture from the existential realm of the divine. The original Sanskrit meaning of avatar was the "incarnation of a god on earth." In virtual reality, the term originated in the mid-1980s with the *Ultima* game series (Morabito, 1986). Within virtual domains, an avatar is the incarnation of a human entity in virtual space; as with Hindu deities, a single human may take up multiple avatars within the same "world," or across them. But these entities are more than human. We describe avatars as "floating" and "flying," signifying powers granted them beyond our own. In myth and dream, from Greek mythology to Renaissance art, the experience of flight has been a universal theme, an expression of our desire for heavenly voyages. In

97

History of Telepresence: Automata, Illusion, and Rejecting the Body, theorist Oliver Grau writes of how "We yearn for omnipresence—a state of transcendence, a variation of gnosis" (2000, p. 235). He suggests that "the idea of the transcendental abandonment of the body follows from the primeval notion of the migration of souls, as expressed in Buddhism or in the *Upanishads* " (pp. 236-237). In cyberspaces such as this collaboratory, we may thus think of ourselves as experiencing virtually embodied and mythic flight in an age of spiritual machines (Jung, 1959; Christ, 1997; Kurzweil, 2000). Given the subject of our work in *Cosmic Voyage*, these experiences were only intensified by imaginatively taking flight among the stars through the Milky Way, because they manifested an ancient connection between the night sky and the brain, between myths and astronomical experiences (Krupp, 1991, pp. 3-4).

Virtual Director™ was crucial to the realization of *Cosmic Voyage*, which was nominated for an Academy Award in 1996. The film has, Director Bayley Silleck and I estimate, been experienced by 6-million viewers (personal communication, 3 December 2008) and continues to be shown around the world, sold on DVDs, and accessed over Internet television providers such as YouTube.   Following this success, we have continued to use Virtual Director™ as a tool to create and collaborate on a variety of visaphor projects (Cox, 1996; Thiébaux , 1997; Cox, Patterson, and Thiebaux, 2000; Cox, 2000ab, 2003abc). We used Virtual Director™ to work interactively in real-time from our CAVE™ at the University of Illinois with scientists and staff at the Hayden Planetarium digital dome in New York City, designing and choreographing camera paths through synthetic astrophysical space. The British Broadcasting Company, which filmed our remote virtual collaboration, named it one of the best uses of virtual reality to date (British Broadcasting Corporation, 2002; see Practicum Compilation DVD, 2:Virtual Tools 2.1). At iGrid2002, we demonstrated an interactive Virtual Director™ remote collaboration

between Dr. Michael Norman located in San Diego, California; Stephen Hawking at his laboratory in Cambridge; and our AVL team in Amsterdam (Brown, 2002; see Practicum Compilation DVD, 2:Virtual Tools 2.2.1 and 2.2.2). Virtual Director™ has been most important to our remote collaborations within recent digital-dome collaborations and continues to provide an important part of our visualization pipeline. Figure 15 shows the Virtual Director™ screen during a collaboration with the Hayden Planetarium. The avatars line up for a ride on the path around the Milky Way model as we work remotely to create a flight through the galaxy
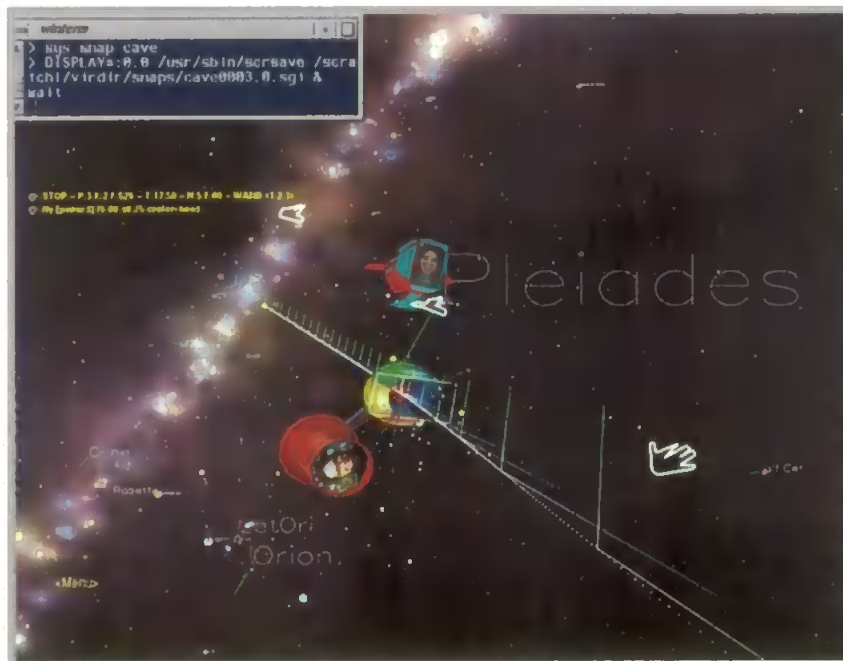
Figure 15. Virtual Director™ avatars on a camera path during a networked collaboration between NCSA in Illinois and the Hayden Planetarium in NYC. Avatars fly through the Milky Way galaxy as they choreograph a virtual Milky Way flight for the Hayden dome show *Search for Life*.

(see Practicum Compilation DVD, 2: Virtual Tools 2.1).

One last word about the artistic orientation and value of this technology: The new aesthetic technology we developed in Virtual Director™ reflects the increasingly democratic and participatory nature of contemporary aesthetics, such as we find throughout new media applications and productions and digital artists' installations. Virtual Director™ enables what Roy Ascott describes as a "global embrace" that is achieved through the emergence of "telematic art" (Ascott, 2003). Comparable functionality has been anticipated by cyber-writers since the early twentieth century (Packer and Jordan,

2001). In Virtual Director™, we sought not only a means for manipulating our virtual

artistic media or enabling collaborating between experts, but also for engaging in

interactive aesthetic play with audiences, across the United States and around the world.

The Hayden Planetarium has used Virtual Director™ for interactive public shows in the

evening, empowering the audience to control the digital dome and the model of the Milky

Way.

Hayden Planetarium and Digital-Dome Projection

In my above account of *Cosmic Voyage*, I have focused mainly on how we enabled

Renaissance Team collaboration through our development of Virtual Director. In this

section, I focus on the role my team and I played in consulting for the projection system

for Hayden Planetarium's new digital dome, which prepared the way for showing our

collaborative productions *Passport to the Universe*, *Search for Life*, as well as the Big

Bang Theater exhibit. Within our field of artistic practice, the projection, transmission,

and display of the work must be carefully designed and evaluated. This is a crucial

dimension of the work to which we give detailed, extensive attention, since it determines

the quality of the audience's experience.

Hayden Planetarium was an early adopter of digital-dome technologies. Funded by

donations and government grants, the American Museum of Natural History (AMNH)'s

Hayden Planetarium in New York City opened its doors in October 3, 1935, making it

fourth oldest planetarium in the United States. Like the Adler and other established

planetariums, the Hayden boasted a Zeiss system that could accurately project locations

and rotating stars, constellations, and other astronomical objects as seen from people on

Earth. By 1993, however, the Museum recognized a need to revamp. The Museum and

donors provided $210 million to build the Frederick Phineas and Sandra Priest Rose Center for Earth and Space, with a new Hayden Planetarium that would become the Rose Center's central jewel. In 1999, the planetarium was outfitted with a Zeiss Mark IX upgrade for the Zeiss projection system, which was then the most advanced available. The star ball could simulate 9100 stars through glass fibers, resulting in white light with ten times the luminescence of Zeiss projectors in most planetariums. However, as is the case with all of Zeiss projectors, viewers were limited to a geocentric view of the universe. Stars and planets rotated on a 2D sphere.

To compensate for this limitation, the Museum installed in the same dome a digital projection system (driven by a Silicon Graphics supercomputer), on which my team consulted. Hayden had sought our expertise and experience with digital projection in part because we had an established reputation for scientific visualizations, especially those generated through supercomputing and Silicon Graphics virtual reality-applications development. We had become involved in this form of applications development in the early 1990s, when the University at Illinois at its Chicago and Urbana-Champaign campuses was pioneering virtual reality and high-speed network connectivity. My team and I had developed Virtual Director™ and contributed to ImmersaDesk (1994) and Infinity Wall (1995) applications developed at the Electronic Visualization Laboratory (EVL, UIC) that also enable collaborations over high-speed networks for a variety of approaches to art and science (Cruz-Neira, Sandin, and DeFanti, 1993; Bryson, 1994; DeFanti, Brown, and Stevens, 1996; Czernuszenko et al., 1997; Leigh et al., 1999; Sherman and Craig, 2003) (see Figure 14).

In 2000, Hayden's digital-projection dome system enabled 3D astrophysical digital imagery to be projected using seven, overlapping, edge-blending, 1280 x 1024 pixel-resolution projectors that merged seamlessly into what was then the highest resolution digital-dome system in the world (Robertson, 2002). The new Zeiss and the modern digital-projection systems project onto an 87-foot diameter sphere (9-million pixels), which is suspended within a mostly glass cube (see Figure 16). The upper interior of the sphere is the space theater (Robertson, 2002). The separate Big Bang Theatre is a smaller space than the main dome, with just four projectors, although at the same quality of pixel resolution. In 2007, the Hayden upgraded the above dome system (Tracey, 2007).

Figure 16. The Rose Center for Earth and Space at the American Museum of Natural History in New York shown above in a cutaway rendition and situated next to Central Park represents the digital full dome upgrade of the Hayden Planetarium

However, through our early collaboration, we helped to effect a transformation with the Hayden creative and technical staff. The Hayden staff visited our team at NCSA in 1998 to discuss the new digital projection system and scientific visualization. During the time when the Rose Center was being built, we visited the Hayden Planetarium to begin planning together sequences and digital imagery that would be used in the first space show there. Once back at the lab, we collaborated with Hayden staff through Virtual Director™, interactively exploring astrophysical simulation data and choreographing specific camera paths for rendering.

Ultimately, we collaborated to create two space shows at the Hayden's new digital dome. These shows were composed of digital-image playback layered with audio and music. The first, *Passport to the Universe*, narrated by actor Tom Hanks, opened at the Millennium 2000 New Year's donor celebration. The second, *The Search for Life*, narrated by actor Harrison Ford, opened in February 2002. Both of these 17-minute long, high-resolution digital shows provided an immersive experience to approximately 440 people, the capacity of the Hayden Planetarium's audience seating. For them, we created digital visualizations of the large-scale structure of the universe as well as the local galactic structure near the Milky Way. Brent Tully, an astronomer from University of Hawaii, provided mapped locations of galaxies from telescopic data. My NCSA team and I created digital images of a voyage through the cosmos arriving at the large-scale structure of the Universe. The shows continue to be popular.

For the Hayden, we also created a permanent installation with the Big Bang Theater exhibit, which occupies the lower hemisphere of the digital-dome structure. The "Big Bang" is a scientific metaphor for the modern story of the first instant of the universe. Modern Big Bang theorists believe that the universe formed over 15-billion years ago when the hot, dense gas that resulted from a massive explosion formed stars and proto-galaxies that congregated along filaments. Astronomers view today's galactic filamentary structure of the universe through telescopes. Choreographer Robert Patterson, software developer Stuart Levy, and I, alongside astrophysicist Dr. Michael Norman visualized over 500-gigabytes of simulation data to show the evolution of the universe following the Big Bang (Figure 7). We repurposed the data used for *Runaway Universe* and we customized a special treatment for the Hayden Big Bang exhibit. (see Practicum Compilation DVD 1:General Visaphor Sequences, Evolution of the Universe 1.6.1). An audience of as many as 200 people can peer over a railing into a large, bowl-shaped digital display to view our

visualization. Looking into the Big Bang digital-display bowl is reminiscent of peering into a boiling caldron in which hot gases produce strings of galaxies. Poet Maya Angelou narrates, while the audience watches the formation of the universe. Ironically, this scientific narrative of creation draws upon the latest technology and scientific theory, thus seeming to authorize this modern creation myth as fact rather than fancy. It becomes a creation story without anthropomorphized agents shaping the universe and our world within it, and yet it is a creation story that can only be told by the creative intervention of cybernetic agents. More discussion on modern creation stories will follow in Chapter 5.

Today, Hayden Planetarium continues to employ Renaissance Teams, influenced by many of the processes that we have established to collaboratively visualize computational science. I strongly believe that such collaborations produce a synergy of expertise that we might call collective intelligence, which helps us to solve complex problems by examining them from a variety of perspectives and experiences. They also drive us to refine our work, to be responsive to audiences from the design to the delivery stages.

Black Holes Digital-Dome Show and Audience Response

One of the primary reasons that an NSF review panel recommended funding for *The Black Holes Project* was because its vision transcended former planetarium productions to incorporate an extensive, large-scale visualization effort directed to a public audience. At the time we proposed *The Black Holes Project*, few other dome outreach programs focused on data-driven visualization. *The Black Holes Project* was the first of its kind to focus its show on the importance of scientific simulation as a new tool for scientists. By featuring the results of scientific simulations as a central component of the

104

scientific narrative, the show brought to public audiences tangible educational benefits

from the art of scientific visualization and computational science (Yu et al., 2007). The

development and design of data-driven visualizations and non-data graphical illustration

sequences for the Gates Planetarium, Denver Museum of Nature and Science (DMNS)

digital-dome planetarium program were afterward revised and redirected to create a PBS

NOVA show, which would reach a larger audience, but one that differed demographically.

The two shows produced for *The Black Hole Project* were directed to different

audiences because the programming for planetariums and PBS NOVA already had

established demographics. These established demographics, moreover, covered the two

poles of popular science education, from the relatively science ignorant to the science

literate. We had a significant pedagogical challenge before us. A primary conceptual goal

of *The Black Holes Project* was to acquaint audiences with gravity, one of the most

compelling forces of our cosmos. In science, gravity is an invisible and powerful force that

affects the experience and evolution of the universe at all scales. In both shows developed

for the project, the contemporary scientific understanding of gravity was conveyed through

the presentation of scientific visualizations, which employed gravitational physics;

scientific illustrations; and story. A historical sequence of discoveries traced the

widespread acceptance of the existence of black holes, arriving finally at how Einstein's

theory of relativity posited a curved space and time in which gravity bends light until light

is non-existent, and the resulting black holes influence the evolution of the universe,

including the formation of galaxies and stars (Boslough, 1985; Kaufman ,1991; Lederman,

1993; Glanz,1998, 2000a, 2000b; Adams and Laughlin, 1999). The shows' narratives self-

consciously highlighted the computational and visualization technologies that have

spawned an intellectual and philosophical revolution in how scientists understand gravity

and our universe (see Appendix for DMNS Promotional Materials and *Black Holes: The Other Side of Infinity* Promotional DVD).

We designed the digital-dome show with a primary planetarium audience of school-age children (accompanied by their teachers and families) in mind. As public institutions, most museums (including DMNS, where Gates is located), provide significant discounts to enable children from diverse backgrounds and poorer school districts to experience planetarium shows. Since the typical time for a planetarium show is 23 minutes--timed to enable the smooth flow of a few hundred people in and out of the theater for each one-half hour of the Museum's business day--we decided that only a few major concepts could be effectively communicated and understood by non-expert audiences.

We designed the planetarium show to give a basic introduction to black holes, but the PBS NOVA show that drew upon materials from the digital-dome show was, in contrast, designed for adult audiences who are classified by the programming staff as "scientifically aware." A project website that provided additional educational materials at both audience levels was timed to open with the NOVA broadcast premier. The content of NOVA websites is coordinated regularly with U.S. national-science-curriculum standards in order to facilitate ease of use in the classroom. NOVA also provided teacher materials for its program through this site (see Appendix and *Black Holes: The Other Side of Infinity* Promotional DVD).

An external agency, Multimedia Research of Bellport, New York, performed a thorough, summative evaluation of the dome show (see Appendix). The agency's summative evaluation was based on randomly selected digital-dome show attendees: focus groups of 6-12 individuals designed to represent a cross-section of the target demographic. The evaluation covered audience responses to scientific concepts, visualizations, narrative flow, and various other aspects of show design. To test the audience's improved

awareness of targeted scientific concepts, their knowledge about them was assessed before and after the show experience. The agency also selected random museum visitors to interview after viewing the show; it continued to track these visitors after, to assess the show's long-term educational impact and affective response. The WestEd Company of San Francisco, California, also performed an evaluation of the effectiveness of the provided teacher materials.

Since the dome show was intended to tour, production evaluation was performed at both small and large planetariums to ensure a broad representation of potential audiences. During production, the project team found a level of audience interest that justified including higher-level content. This approach was later validated by the results of the summative evaluation for audiences in the lower-age range. According to the report, viewing the show "significantly increased 4th and 5th graders' understanding" of black holes. Before viewing the show, only 12% -16% of students gave correct answers to the questions "What is a black hole?" and "How do scientists know black holes exist?" After viewing the show, those numbers jumped to 60% and 63% respectively. The study concluded that the show "successfully both entertains and educates the upper elementary age student" (see Appendix; Flagg, 2006, p. 217-235). We credited some of this success to production testing, which had identified problem scenes and given us an opportunity to revise the clarity of their message.

During production testing, we also learned that audiences (unanimously) wanted to know when they were viewing data-driven scientific visualizations that have been developed with numerical models, rather than concept illustrations that have been drawn without such rigorous data mapping. The focus group unanimously agreed that they wanted to know the difference between scientific data and an illustration. We changed the script to accommodate this evaluation, which, for us, validated a key purpose of the show.

107

The later NOVA show received its own evaluations during production and after. Most production testing was conducted by Tom Lucas in cooperation with NOVA staff, and funded by NASA's GLAST project. AVL staff and I participated in this iterative review process. Prior to beginning principal photography, Multimedia Research sent the treatment to independent, expert reviewers. They commented on the clarity of the presentation, the strength of its story lines, and its probable achievement of overall science education goals. Once the program had been assembled into a rough cut, it was shown to adult and high school focus groups across the United States. This summative evaluation, performed by Knight-Williams Research Communications of Sacramento, CA, had the goal of determining how audiences responded to both the overall story and individual scenes for clarity and effectiveness of presentation. Focus groups were also asked to consider specific elements such as the scientific visualizations, graphics, on-screen characters, and attractiveness of the content. Audiences judged that the NOVA program was a success. Knight-Williams Research's final report found that "The program addressed many difficult and abstract science concepts, yet was still enjoyed by and successful with a diverse viewing audience, one that extended beyond the traditional PBS viewer, science/nature show enthusiast, or astronomy buff"(see Appendix; Knight-Williams and Williams, 2007, p. 237-258).

Chapter 3: Scientific Visualization in Translation: Understanding Visaphors as Metaphorical Interactions and Autopoetic Systems

Linguistic and visual metaphors recombine like DNA to provide a rich cultural environment in which scientific narratives proliferate and thrive. Visaphors are a distinctly modern, high-tech art form, but the metaphoric process through which they are constructed and understood has been a topic of study and debate since ancient times. From the recorded beginning of that conversation, we can trace a radical split between logical positivists / realists and relativists / constructionists. In early debates in mathematics between Plato and Aristotle, for instance, we find these oppositions: on the one hand, math is an organizing principle found in the universe; on the other hand, math is a construction of the human mind. In the first chapter, I established the bias toward logical positivism and hard realism within the data-viz community and argued the value of broadening our view. In this chapter, I explain the foundation of relativist / constructionist understandings of metaphor and establish how such an understanding can enrich our sense of visaphors.

In the first half of twentieth-century Western philosophy, logical positivists such as Bertrand Russell held that precision in literal language and mathematics was the most appropriate tool for describing reality and doing science (Whitehead and Russell, 1910-1913). To such nonconstructivist thinkers, metaphor was a linguistic trick that obscured our ability to discover "true" reality accurately; it was not appropriate for scientific discourse. In contrast, the constructivist position has held that epistemological access to reality may be found through mental construction. Constructivist psychologist Jean Piaget theorized that children develop in stages through a process involving mental constructions: "To invent is to combine mental, that is to say, representative, schemata and, in order to become mental the sensorimotor schemata must be capable of intercombining in every way, that is to say, of being able to give rise to true inventions" (1936, p. 341). Reality for

the constructivists with whom I align myself is always mediated through minds and bodies. Human knowledge and its signifying systems, such as language, are considered essential dimensions of this mediation of experience, its comprehension and record, although some thinkers claim language is formative to thought and some mark it as an after-effect. Wittgenstein's later work, which also stands in opposition to logical positivism (Wittengenstein, 1953), is thought to have initiated the linguistic turn. From this position in 1953, Benjamin Whorf argued that language shapes the worldview of its speakers.

Modern metaphor studies come to us by a different route, through I.A. Richard's iconoclastic and positivist rejection of rhetorical studies' understanding of metaphor as a device, a purely linguistic phenomenon (Black, 1962; Richard, 1965; Sacks, 1978). In Richard's 1936 lectures on the philosophy of rhetoric, he declared a connection between verbal metaphor and thought: "Thought is metaphoric, and proceeds by comparison, and the metaphors of language derive therefrom" (Richard, 1965, p. 94). Richard sought to expand metaphor theory into a science and opened the philosophical door that resulted in an interdisciplinary theoretical discourse. By the 1960s, Max Black argued against Russell, Wittgenstein, and Whorf, introducing his interaction theory of metaphor. Black's view engendered a broad dialogue, eventually exposing the study of metaphoric processes to the scientific light of cognitive studies.

In the second half of the twentieth century--with the advent of computational science and digital visualization, and with the success of math-based systems for describing the world in all its material and immaterial phases—we might have expected some kind of resolution to the debate between constructivists and positivists. However, it has not proven possible to reconcile this great divide. As a result, these polarities continue to be reflected in contemporary discourse on thought, language, and metaphor. Over the last five decades, researchers have generated more than 10,000 articles and books on

110

metaphor and related studies. Most of these writings have followed in Richard's tradition, focusing on linguistic metaphor and its expression of cognitive processes.

Beginning in the 1980s, George Lakoff and Mark Johnson famously re-contextualized metaphor as being more about how people cognitively process thought than how we verbalize it; this paradigm shift enabled a constructivist position within metaphor studies. The landmark work of George Lakoff and Mark Johnson, *Metaphors We Live By* (1980), demonstrates how metaphorical ideas can become embedded in culture: we become unaware that they shape our reality and, simultaneously, limit possibilities. For example, Lakoff and Johnson argue that Western European cultures habitually understand and communicate the concept of "mind" (1999) through contemporary, everyday language. They expose the metaphorical correlates that provide the basis of Anglo-American analytic philosophy and the linguistic foundations of assumptions that thought can be represented by mathematical, logical symbols. In *Metaphors of Memory,* Douwe Draaisma visually demonstrates cultural metaphors of mind throughout history. In particular, he argues that cultures and individuals reflect popular preoccupations through their metaphorical inventions, often attempting to understand or explain the brain in terms of the newest technology domain. He demonstrates a variety of historical metaphors for operations of the mind (2000). In the industrial age, mind was both a machine and an electrical transmitter and conductor. When cinema was new, the brain was described as working through cinematic processes, such as projection and registration. Now, we tend to describe the brain as a computer. This, too, although a useful figuration runs the risk of limiting our conception of the brain and so may limit studies in cognitive science and related disciplines (as we shall see in Chapter 4). In my view, the brain is much more than a computer; the metaphor fails to capture the scope of human agency.

Today Lakoff and Johnson continue to articulate the terms in which metaphor is most discussed. The dominant understanding of metaphor derived from their work is that of concept mapping, which focuses on metaphor as a cognitive process by which we understand one domain of information in terms of another. We map context-dependent properties from one concrete expression to another, both of which are richly defined (denotatively and connotatively) within systems of beliefs, or concept networks. In other words, a metaphor triggers interpreters to comprehend the target domain in terms of the source domain. This partial and directional mapping of properties from concept networks, called "highlighting," is not comprehensive, but selective, and not arbitrary, but determined by preconceived cultural understandings. It is within this trans-domain mapping process that new meaning can be generated (Black, 1962).

In *Philosophy in the Flesh: The Embodied Mind and a Challenge to Western Thought*, Lakoff and Johnson provide detailed analyses of linguistic metaphors and their genesis to create a sort of DNA map of basic conceptual metaphors and their relationship to culture and consciousness (1999). Lakoff and Johnson provide convincing evidence that much of our conceptualization and related linguistic metaphoric representations of the world have evolved from our embodied experiences. They claim conventional metaphors (as opposed to creative, or inventive, ones) are embedded in our culture--the equivalent of socially embodied experiences--to the point that we interpret their meanings literally. They give "time is money" as an example of a conventional metaphor that has become embedded in American culture. We understand time in terms of money and conceptualize time as being "spent," "saved," or "wasted." Such basic, conventional metaphors help structure our everyday thinking and behavior. For example, "argument is war" formulates how we think about arguing. We "defend," "strategize," "attack," and "defeat" arguments.

112

If our culture had adopted "argument is illness," then an argument would be "diagnosed" and "treated" (Lakoff and Johnson, 1980).

Ultimately, Lakoff and Johnson's work maximally stretches the theory of metaphor: Here, "reality" becomes a metaphorical mapping and all knowledge is gained through the embodied experience of this mapping. Even positivist methods for arriving at assessments of the real, such as mathematics, can be viewed as embodied metaphoric constructions derived from experience (Lakoff and Nunez, 2000), thus preparing us to view data-driven visualization and scientific mathematical models not as objective (natural, real, true, static) depictions that mirror the real, but as representations of an experienced reality that are socially and, so, perceptually mediated. Whereas Lakoff has primarily been concerned with the verbal and conventional end of this range, visual metaphor theorists have primarily focused on the figurative, or novel end, of it (Gombrich, Hochberg and Black, 1972; Forceville, 1994, 1996).

Indeed, metaphors can be generative, as well as derivative. In *Metaphor and Cognition: An Interactionist Approach*, Bipin Indurkhya introduces the metaphoric content-continuum as a spectrum from the most familiar, literal conventional metaphors to novel, figurative metaphors (1992). Verbal metaphors such as 'books are fresh fruit' are more figurative and novel than "time was well-spent," which is interpreted as literal language. Most theorists agree that novel metaphors can eventually evolve to become conventional as a culture accommodates the metaphor and reduces novelty to literality.

I extend the metaphoric content-continuum to visaphor creative process, especially in associating standardization and consistency with literality. New, data-driven visual tropes eventually evolve into conventional methods through audience consumption and recycling. For example, CGI Doppler maps are now mainstream media aids in weather news around the world. These visual tropes were introduced into popular culture after the

113

advancement of Doppler radar and its by-products in World War II (when it was used to activate proximity fuzes). Audiences acclimated and absorbed these forms into their conventional visual language. For example, the data-driven visaphor in Practicum Compilation DVD 3: Hunt for Supertwister, Scene 5, Sequence 3 shows how computational data from an F3 tornado can be visualized in a two-dimensional pseudo-colored slice that emulates familiar Doppler weather maps. The novel visaphor of a computational tornado engenders an absolutely fresh perspective of a tornado, an almost arresting view to some who first see it immersively, as we are told. However, the more familiar Doppler–based visual enables audiences to recognize and comprehend some features of this novel visaphor more quickly and easily. As novel visaphors are consumed, absorbed, and recirculated--as Doppler maps have been--they too will move to the more conventional range of the metaphoric content-continuum. The visualization artist is empowered through both technology and imagination to create anything across the range of conventional to novel visaphors, even though the underlying data may remain consistent. A target visaphor can be designed to fall at different points along a metaphoric-content continuum from conventional, which tend to be taken literally and rationally, to creative, which engage viewers in active, emotional, and often more intuitive processing. I will use the IntelliBadge™ project to show how my team and I created visaphors that span the metaphoric-content continuum. IntelliBadge™ was a special radio frequency people tracking project funded by NCSA, IEEE, and vendors (Cox, Kindratenko, and Pointer, 2003). In Figure 17, I compare two IntelliBadge™ visaphors designed to show real-time data changing during the radio frequency location-tracking of conference attendees (see Practicum Compilation DVD 1:General Visaphors, IntelliBadge™ Project Visaphors, 1.1.2 and 1.1.2) Figure 17 shows two separate layouts for visualization displays distributed throughout the convention center. People self-selected from ten categories of interest at the

114
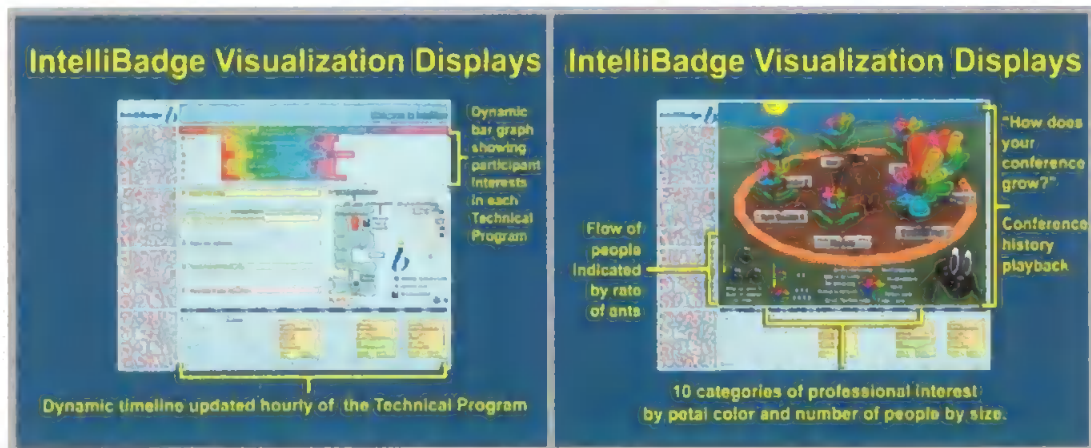
Figure 17. IntelliBadge™ visualization displays show real-time data being updated every second during a conference. Radio-frequency tags track people and provide data to visualize movement with two different metaphors: On the left display, the dynamic bar graph and on the right display, "How does your conference grow?" Both use ten discrete colors to indicate ten categories that represent peoples' interests.

conference. Each of the categories was assigned a distinct color. This identical data is represented using two different visaphor schemas (Figure 18, above and below). The

source domain for both visaphors is a real-time, changing numerical database that tracks people (via radio frequency signals) who have been coded according to their main interest group as they move within a convention center. Compare Practicum Compilation DVD, 1: General Visaphor Sequences, IntelliBadge™ Visaphor Project, 1.1.1 and 1.1.2. In Figures 17 and 18, a dynamic, multi-colored bar

Figure 18 The garden metaphor above: each flower indicates room location; each petal indicates a category of interest of people moving throughout the conference rooms. Flower and petals scale as people move in/out of rooms. Ants move at the rate people move. Below, the bar graph employs identical real-time data and color categories.
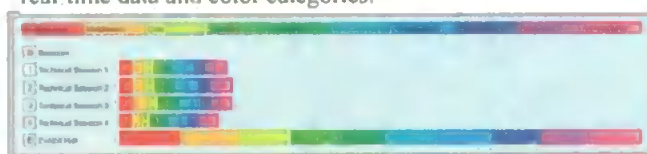
chart depicts the distribution of aggregate professional interests of people moving through

six areas at a convention center: ballroom, four technical sessions, and the exhibition hall.

Colors correspond to areas of interest, such as blue for "visualization" and magenta for "applications." The same tracking data is mapped to a visaphor called "How Does your Conference Grow?" in Figures 17 and 18. Each room is represented as a flower; the colored petals shrink and grow according to the flow of people entering and leaving the rooms:

total aggregate professional interests in "data" → length of yellow in bar graph

total aggregate professional interests in "data" → size of yellow petal in flower

The dynamic, digital bar chart in upper (Figure 18) is a conventional visaphor. Despite novel beginnings, bar charts (as well as graphs and maps) have been used in our visual culture for so many years that they now constitute a literal translation of data. Although these visual tropes can be used poorly, they still comprise one of the most common graphical means to present "factual" data (Tufte, 1983). In contrast, the botanical, iconic representation is a figurative, novel visaphor. The garden visaphor's freshness transports viewer imagination beyond the familiar to ideas they had not thought possible to experience. Audience participants in the IntelliBadge™ Project provided exceptional and positive feedback in response to the garden visaphor. We informally interacted with viewers and captured some of their interactions on video (see Practicum Compilation DVD, 1:General Visaphors, IntelliBadge™ Project Visaphors, 1.1.3). We have provided this demonstration to numerous audiences. They describe the garden metaphor as "delightful," "fun," "playful" and "surprising." Analogizing attendees who were rushing through the conference convention center as ants was particularly endearing. This novel visaphor widened attendees' view of what constitutes data visualization by visually associating familiar social behaviors with novel graphics. Through conventional and novel

116

visaphors, identical data revealed that attendees spent most of their time in technology exhibits rather than lectures. However, it may be that viewers' interpretation of convention behavior was affected by whether they viewed the flower or bar chart. Although the scientific measurement of audience response to differing visaphors awaits future research, for my purpose here, the point remains. The same quantitative data can be creatively mapped to alternate visual models; the artists' intent empowers that process. In "How Does Your Conference Grow?" visaphors portray attendees' movement through space through actual, real-time data; at the same time, attendees' responses to environment are creatively recontextualized through visaphor.

Meaning, metaphoric or otherwise, cannot be made in a vacuum; it is an inherently social process. Here, I find it useful to examine communication and meaning in relation to information theory, since this is the dominant theory in computer science today. In *The Mathematical Theory of Communication*, Claude Shannon and Warren Weaver (1949) demonstrated the efficacy of a quantitative approach to information theory. A broad range of disciplines continue to employ and improve upon the underlying mathematics today, especially in the information technology domain of computer science. Applications areas include mass telecommunications, mobile communications, computer information systems, bioinformatics, and computational linguistics. The original theory employed many verbal metaphors that have become popular concepts in how we think about communication today. For example, we "transmit messages" and "receive signals." However, Shannon and Weaver never intended the term "information" to include meaning: "The word *information*, in this theory, is used in a special sense that must not be confused with its ordinary usage. In particular, *information* must not be confused with meaning" (p. 8). Within this information theory, messages are distinguished in terms of transmission. From an engineering point of view, signals are treated the same whether they are loaded with

meaning or nonsense (Reddy, 1993). The mathematical approach to information theory has been undeniably successful in computational applications; however, in real-world studies of communication, this one-way signal processing is deficient in helping us to understand how complex images are understood as information.

In contrast, Forceville adapts his theory from psychology and communications research, taking into account three key sites of meaning-making: human agency in communicators, information context for the message, and active interpretation in audience members (1996, pp. 67-82). Given this theory, the process of creating a visaphor, data is organized into information with the intent to inform. However, human agency must be considered at the transmission and receiving points of the communication process as well, since visaphors are consumed in a variety of circumstances and they often help to provide a new world view. People "read" visaphors in different ways depending upon the context of the presentation and their own orientations toward information and context. Thus, the intent to inform may or may not be successful, and information can be lost. This aspect is particularly relevant when considering presentation forums such as the Hayden Planetarium or Public Broadcast Service television. However, the intent to inform, to transmit data, so that it is accurately received by an audience, is a limited and limiting way to understand communication, whether scientific, artistic, or a hybrid of the two.

Interactionist communication theory adds to our understanding of how metaphor affects the generation of knowledge, which includes not only information, but information within a system of associations, both denotative (definitional) and connotative (ideological, associational, and emotional / atmospheric). Interaction theories in cognition studies sometimes take a constructivist point of view. In *Metaphor and Cognition: An Interactionist Approach* (1992), Indurkhya addresses the greatest paradox in the constructivist view of cognition and metaphor. How is it that humans construct reality and

access reality through filters of language and culture and at the same time are constrained by the structure of an external world? Most interactionists and constructivists deny a pre-existing structure of the external world, yet recognize the constraints of the physical. This is a contradiction and paradox that Indurkhya attempts to clarify in his interactive cognitive network approach. His study in cognitive systems and metaphor takes the view that cognition is a process of interaction between a cognitive agent and its environment. The cognitive agent constructs the world by building cognitive concept networks, but this construction is not arbitrary. Although Indurkhya acknowledges that concept networks must respect the ferociousness of reality, he adheres, finally, to the position that all knowledge is metaphorical. This thesis employs Indurkhya's analysis to dissect why the creation of visaphors can be metaphorical, culturally contingent, yet non-arbitrary and effective. Given the domain of digital data, however, visaphors pose yet another layer of complexity that Indurkhya does not address. His study is limited mainly to verbal metaphor; it only touches on the non-verbal in a disappointingly cursory manner.

Charles Forceville's *Pictorial Metaphor in Advertising* (1996) employs Max Black's interaction theory to provide one of the most complete analyses of visual metaphor to date, although Forceville limits his study to billboard content. Since Forceville assumes advertising is an attempt to communicate a message, he is predisposed to consider the explicit communicative nature of visual representations. Forceville claims that techniques such as the verbal anchoring and contextualization of images help to determine how viewers understand a visual metaphor's message. These visual conventions send (typologically) generic cues to viewers, invoking viewing protocols that help them to interpret the visual messages in already normalized ways

In visual terms, Forceville analyzed the mapping of characteristics from a visual source domain onto a visual target domain. For example, an advertisement shows a person

with a pair of earphones that look like bricks. The text of this advertisement and the visual

juxtaposition imply that most earphones are heavy and that the earphone product being

advertised would be light. Viewers cognitively select characteristics from the conceptual

domain about "bricks" (source domain) and map these characteristics onto the conceptual

domain about "earphones" (target domain). This mapping process is partial and non-

arbitrary. We do not map the "bricks" characteristics of "clay baked" or "rectilinear."

Rather, we get a new understanding of "earphones" in terms of "bricks" by mapping

"heavy, hard, and uncomfortable" (Forceville, 1996, pp. 126-129)

As with the visual advertisements that Forceville analyzes, visaphors target specific

audiences and are meant to communicate. Although most discussions of visaphors focus

on what and how they communicate literally, they too convey emotion and indirect

ideological content. Visaphors may also range from the literal to the figurative, and they

may be presented across a broad spectrum of media, from television to periodicals, which

impact how they are presented, who their audiences are, and how their audiences may be

trained or inclined to view the material. Visaphors--again, like advertisements--draw upon

a broad range of conventions to generate meaning and guide interpretation, such as those

that govern representations in the sciences and those borrowed from other domains,

including the commercial, political, and humanist.

Display media provide yet another substrate for determining how visaphors

communicate meaning. Visaphors can be interactive software applications as well as

digital animations. Visaphors can be displayed on a variety of devices that range

from a stereo, rear-screen projection CAVE™ to QuickTime movies. For the purposes of this thesis, virtual reality and other mixed realities are alternative physical display systems where visaphors are presented. Other physical displays include large-scale digital projection domes, IMAX theatres, passive stereo theatres, digital reality theatres, television screens, and print media. For example, Figure 19 shows the tornado visaphor being used in print media for the cover of the President's Information Technology Advisory Committee Report (Reed, et al., 2005), as well as being shown on advanced 4K stereo research projectors at a JVC exhibition in Japan. These varieties of display media provide powerful

Figure 19. Mobility of Visaphors: above is the cover of the President's PITAC report; below visaphors are playing on a prototype 4K stereo display with JVC R&D in Toyko, Japan.

experiential impact and context to visaphors; however, the primary focus here is on the creation of visaphors in the art of computational scientific visualization and the ways in which they embody and communicate meaning metaphorically, through the aesthetic choices of the artist within specific discursive and social contexts: a post-industrial, American culture in which scientific communications and its popularization elide the constructed nature of scientific discourse, even as they foreground narratives of scientific

discovery and technological progress that challenges and retools received human knowledge, agency, and experience. (I discuss the *The Black Holes Project* display of visaphors in a digital-dome context in Chapters 2, technically, and 5, metaphorically.)

How, then, can we better understand visaphors through taking up the constructivist view of metaphoric processes and, in particular, Lakoff and others' claim that metaphoric mapping is the very process through which we structure our epistemologies, such that our sense of reality itself and all the ways we chart it are determined by metaphorical maps? I begin to answer this question with a return to Lakoff and Johnson. According to Lakoff and Johnson, many cognitive functions and structures, and most operations, are below our conscious awareness, residing in the cognitive unconscious (1999, p. 3). For example, our visual and auditory processing systems are formed by complex neural connections and physical electrochemical interactions of which we are unaware. From fundamental associations of our bodies, such as looking up, we formulate higher-level concepts. Our daily language, it has been demonstrated by Lakoff and Johnson, is linked in layers of metaphorical maps that refer to early spatial orientations, with our gravity-bound, planetary experiences among them. We might call these "experientially-grounded" mappings (Lakoff and Johnson, 1999, p. 47). The experiences we humans share in common, universally—experiences of our very embodiment, such as the weight of gravity--are expressed through linguistic structures across languages. These are what Lakoff and Johnson term "primary metaphors."

However, we also create complex metaphors, ones that cross conceptual domains, through bootstrapping higher levels of abstraction from the lower- level metaphoric structures that are most closely connected to our sensorimotor capacities. Complex metaphors are those that are most often used to capture emergent ideas. What is most significant for us here is that visaphors are often complex, built by data-viz artists from

primary metaphors to help theorize and communicate theorizations about highly interactive and multidimensional processes. The visaphors that I create and present are founded in the computational scientific process, which are themselves complex, multidimensional, and ever emergent. We shape our reality through such conceptual maps, with the mind generating their formal structures and our thoughts giving them dimension and depth. In this way, the body is not involved in perception merely as an elaborate, organic sensory array; the body shaping conceptualization at its very root, determining the very nature of metaphor and the reality it at once describes and makes possible (Lakoff and Johnson, 1999).

A crucial claim here is that the embodied mind does not distinguish between perception as based within bodily senses and sensory data that are engaged during the process of conception (i.e., the generation and use of concepts). In other words, conceptualization, too, is a bodily process--not a separate mental function worked through in some disembodied, super-effect called consciousness. We find this notion of an embodied mind and its construction of embodied reality reflected in Lynn Margulis and Dorion Sagan's *Microcosmos* evolutionary theory of the human brain as symbiotic: a complex bio-organism with a higher purpose, awareness, and complexity of existence that has evolved from individual cells that organize, cooperate, and interact (Margulis and Sagan, 1986). Margulis has argued, for example, that orientation-sensitive cells are a part of the brain's visual system and that the complexity of our brain has evolved through the cooperation and symbiosis of these cellular colonies. Thus, spatial-conceptual relationships, the kind reproduced in primary metaphors, may in fact be an emergent property of the symbiotic brain. Sensorimotor responses and cognitive metaphoric conception may be linked through a biological lineage to primal connections over millions of years of cellular differentiation, symbiosis, and evolution. Perception and conception,

123

then, are integrated embodied experiences. The study of the color visual system, in particular, helps to establish this connection. "We have seen that basic-level concepts depend on motor movement, gestalt perception, and mental imagery, which is carried out in the visual system of the brain," Lakoff and Johnson write.

> "We have seen that color is anything but purely mental, that our color concepts are intimately shaped not merely by perception as a faculty of the mind but by such physical parts of our bodies as color cones and neural circuitry. And we have seen that spatial-relations concepts are not characterized by some abstract, disembodied mental capacity but rather in terms of bodily orientation." (1999, p. 37)

This new understanding of complex metaphors as products of an embodied mind makes possible a sense of how visaphors not only reveal relationships between primary metaphors or simulate and communicate complex information, but also how they can expose emergent systems of both meaning and matter, systems that can be further explored for their own interactions and synergies. In *Gödel, Escher, Bach: An Eternal Golden Braid* (1979), Douglas Hofstadter discusses how subtle trends within fields that express neurological structures--mathematics, symmetry, and intelligence--reveal that self-reference allow systems to acquire meaning. Though I differ with Hofstadter's formal logic approach, which simply equates cognitive functions with software components, I agree with his "strange loops" metaphor with which he characterizes emergent phenomenon at many different levels of a complex, hierarchical system. "The 'Strange Loop' phenomenon occurs," he writes, "whenever, by moving upwards (or downwards) through the levels of some hierarchical system, we unexpectedly find ourselves right back where we started" (p. 10). Consciousness is a self-referencing strange loop that emerges from clustered, hierarchical components. Strange loops pre-date Varela's autopoetic embodied mind or Margulis' evolving symbiotic brain, yet the underlying premise remains the same. To make his point, Hofstadter creates an analogy between an ant fugue—in which a colony of ants acts as a unit, but is made up of individual members—and the

124

mind—in which its component parts chime together to produce the epiphenomenon of consciousness.

We find such metaphorical coherencies in other simulations of natural phenomena within the field of the data-viz arts. For example, when scientists study tornadoes in the atmospheric sciences, they tend to see the component parts in a system (e.g., wind temperature, pressure, velocity, direction) coming together to create the unit, or epiphenomenon, of the tornado. The scientists who study a tornado event become so taken with it as a whole and separate entity that they discuss it in terms of its birth and death, its being and power—as if each tornado were a living thing, complete unto itself.

When we visualized a tornado for the PBS *Hunt for Supertwister,* we metaphorically mapped data about its physical components and their behaviors to numerical models in the attempt to understand how a tornado forms. In the resulting simulation, complex processes came together into an overarching unity that we labeled "tornado." The numerical model might be viewed as a mathematical mapping of a collective experience we conceptualize as weather. The numerical model may also be seen as providing the source material for yet another metaphorical mapping of a constructed experience into a visual artifact, a visaphor. The brilliant colors, the geometric shapes, the evolving flow visaphorically recapitulate a collective, metaphorical consistency upon which humans can collectively agree through their cyberception, i.e., technologically-augmented perception.

The visaphor is a tool, an invention, and a technology--like writing or mapping--that both refuels and reinforces our concepts about a tornado. The visaphor of a tornado shows the interaction of all these colorful, abstract processes through a trans-disciplinary, creative practice that incorporates current scientific assumptions, mathematical modeling, movie-making techniques, and embodied experience of human beings. Yet where does the

125

tornado begin and end, and how do we locate its singularity, its coherence? The tornado is the collective of many components that we experience according to our level of understanding and our scale of experience. The tornado as a thing in itself is a property that emerges from large-scale processes in atmosphere. Like eddies in a pool of water, tornados may arise and pass away within a larger body of natural forces. Yet the tornado as a force, a power, affects its surroundings and environment. One of our great scientific challenges is to integrate an understanding of small-scale features, like a tornado, into large-scale geological and atmospheric processes, incorporating such phenomena as ocean temperatures and solar winds. Yet, beneath the powerful swirl of tornadic events, nano-phenomenon also emerge in their own worlds as separate layers of existence, as processes of strange loops that are infinite in all directions. As is the case with all natural phenomena, here we see interacting layers of autopoetic systems. Biodiversity is replete with examples of overlapping, self-maintaining systems, nested within each other. Organisms survive upon the continental shelf to survive within the gut to survive within the human to survive within society and its technological dynamic to one day exist on a planet within the solar system in a galaxy far away. The interaction of autopoetic systems, and their integration of increasingly higher (and lower) levels of organization, can be seen throughout all of life and the universe. To express the magnificent branching structure of this intellectual, conscious ecology of autopoetic systems, Hofstadter uses the metaphor of a chiming, repetitive, and coordinated audio pattern of a musical fugue. The many act as one in concert. A symbiotic unity is born of an accumulation of operations of many individual components, like an orchestra with different instruments that all resonate together. Because of their visual metaphorical layering, visaphors have a special aesthetic capacity to express the complex dynamism of autopoesis, especially when animated.

The creation, propagation, consumption, recirculation, and repurposing of visaphors may also be considered an autopoetic system, one I will refer to viseotelecommuning. Viseotelecommuning is the feedback mechanism through visualization that feeds and reinforces conceptual metaphors in culture. In life, it is the process of the universe looking at itself, the co-opting of bio-organisms and technology to collectively reflect the stories that we tell about our understanding of the universe and ourselves. The audience is made up of bio-organisms that internalize sensual and intellectual experiences through their cyberception (Ascott, 1994, 2003) and retransmit them to collective culture through casting their own cybernetic tentacles over cyberspace. Through visaphors, we shape the environment, and we are shaped by it. Visaphor audiences are not only carriers, but they are also catalysts. They visually, intellectually, technoetically devour; they regurgitate, replicate, and disseminate. Through viseotelecommuning, biological beings and their intellectual, techno-scientific offspring participate in a grand cyberceptive cycle of collective invention and reflection.

cycle of data and constructed conceptual reality:

perceived input data → construct conceptual model → build visual model or artefacts → public presentation → increase support and funding for world view → build technologies and instrumental data → simulate models of nature → construct theories → output physical models → share and test models → modify conceptual maps → modify perceived reality → modify input data

Viseotelecommuning has been ongoing since humans first invented and used tools / technology to make artifacts imbued with predictive powers, whether mystical / magical, or scientific. The same process at work in this hybrid domain between the arts and sciences

is found in myth making; like myths, visaphors are fundamentally engaged with defining cultural narratives. Such collective accounts of existence even share basic structures for organizing relations between what are perceived as essential states of being: tree-forms and hierarchies. Through visually harnessing metaphor's power to transform disparity into coherence, visaphors establish a cognitive telecommunion between our embodied minds and our social myth of the real.

Chapter 4: An Emergent Scientific Paradigm: Visaphorizing Our Evolving Consciousness

The traditional view of the history of science describes scientific progress as a series of men and women developing better methods to do science. The dominant narrative traces--from Galileo to Newton--an advance from observation and experimentation to theoretical research. Revisionist historians amend this view with sociological and paradigm-shifting significance (Kuhn, 1962; Holton, 1973; Latour and Woolgar; 1979; Stepan, 1986; Jaki, 1990; Martin, 1991; Keller and Longino, 1997). While some empiricists have recognized and feared the power of the scientific image--tending to view visualization as a negative process whereby scientific objectivity is lost --many more have ignored the influence and popularization of visualization in science (Lynch and Woolgar, 1990; Baigrie,1996).

The Importance of Visualization to Science

The history of scientific illustration marks the importance of visualization to the development of the sciences, not only for pedagogical demonstration, but also for cognition, theorization, propagation, and promotion. Visualization--defined as the process of creating and using images and visual models--has been employed by great scientists since our earliest efforts to philosophically and practically study the natural world. Before the computer, hand drawings and diagrams served as conceptualizing, documenting, and didactic tools for early science. Historical scientific illustrations bifurcate into two primary types: those that represented natural phenomenon, such as drawings of plants, and those that represented more abstract concepts, such as tree diagrams (Brown, 1996). This bifurcation echoes the split in data visualization: scientific and information visualization.

Text accompanied the most important, unforgettable illustrative visualizations. As printing technology evolved, the sophistication and proliferation of illustrations evolved. Historians of these early scientific visualizations often oppose an empiricist account of scientific progress that suggests only experimental observation has been of value to the evolution of science since the seventeenth century. Many historians of science have successfully argued that artists' concepts and imagery have helped to form scientific knowledge and methodology--that images can serve, and have served, as positive, functional elements in scientific epistemological formations (Grombrich, 1973; Topper, 1996; Hallyn, 2000; Brown, 2003). Others have also made the case for the contributions of visualization to the formations of specific scientific disciplines such as archeology, geology, and chemistry (Knight, 1996; Moser, 1996; Ruse, 1996).

Not surprisingly, the Renaissance, with its revival of classical learning and renewed interest in the study of nature as such (expressed as material, and not just spiritual, phenomena), was a watershed for the use of scientific and technological illustrations. The wide use of scientific illustration during the Renaissance suggests, even then, a dynamic interplay between image, science, and the public. The role and influence of visual models upon the process of conceiving, developing, and communicating scientific knowledge is well documented (Hall, 1960; Latour, 1979; Jones, 1990; Caudill, 1994; Peterfreund, 1994; Baigrie, 1996; Brown, 2003). During the sixteenth century, botanical, anatomical, and biological books with illustrated text proliferated. Copernicus, Kepler, and Descartes created drawings and visual models that not only documented observations, but also augmented understanding and conceptualization. Historians have argued that artists' concepts and imagery helped to form scientific knowledge and methodology during the Renaissance, and artists directly contributed to the popular view of rendered reality during the period (Topper, 1996).

130

From the time of the Renaissance forward, scientific illustration has continued to play a major role in scientific study, education, popularization, and promotion. The nineteenth century was another important developmental period in the search for visual structure in science and nature (Crary, 1990; Alverson, 1991). Many of the representational devices developed then are incorporated in modern, data-driven digital visualizations (Novacek, 1994; Woolman, 2002). One such instance: Darwin's representation of natural systems as tree-form diagrams, such as phylogenetic trees. These tree-forms remain a part of the visual language of geneticists today, although sophisticated digital technologies have replaced crude drawings to re-visualize genetic systems (Figure 2). As technology has progressed, scientists have also come to employ photographic imagery from instruments such as telescopes and microscopes. By the twentieth century, radiography flourished, coupled with computer image processing techniques. Many scientific fields advanced with the use of radiographs, from medicine to crystallography.

The practice of visualization was also impacted by the ubiquitous influence of Hierarchy Theory, which grew as an interdisciplinary way to organize and describe forms and processes in nature, physics, and complex systems. In *Structural Hierarchy in Science, Art, and History*, Cyril Stanley Smith defines hierarchy not as a power principle of master to slave, but rather as an ordering pattern found throughout the universe. In fact, Smith posits a balance between "anarchy" and "hierarchy": "It would be good to avoid both terms for they are overloaded with political emotion, but I know of no better word than hierarchy to convey the idea of an interpenetrating sequence of structural levels" (1978, p. 11). Branching and bifurcation are, for example, structural patterns that are ubiquitous in nature, radiographs, scientific and mathematical models, and technological structures (Whyte, 1951; Whyte, Wilson, and Wilson, 1969; Auger, 1986; Feekes, 1986;

Ahl and Allen, 1996). This attempt to organize forms and processes has grown directly from the onslaught of technology-mediated scientific images.

We now live in a golden age of scientific visualization. Yet, even those scientists who value and employ scientific visualization in their own work, and who support its use in popularization efforts, tend to view visualization as a transcription of the empirical real. Visaphors are usually viewed as having a specific, self-evident intent by their creators to quantify, qualify, and convey digital information in visual form. They are valued for their ability to map mathematical models accurately, to display as realistically as possible actual phenomena, to expose an aspect of material substances and forces as they are known (or theorized) to exist or occur. Scientific authorities made anxious by challenges to scientific "truth," and eager to assert their own claims of scientific advancement, are thus all the more inclined to police a perceived boundary between (objective, evidenced) fact and (subjective, constructed) fiction, as well as contributions to science made by approved experts, as opposed to those made by their collaborators from outside fields.

Mediating Perception: From Tele- to Digi-Epistemology

In the philosophy of science and technology, we can identify a paradigm shift in the nineteenth century from unmediated observational methods toward an extreme reliance on technology-mediated empirical methods for defining the real--what Don Idhe calls "instrumental realism":

> "The focal point at which instrumental realism emerges is the simultaneous recognition of what I have called the *technological embodiment* of science, which occurs through the instruments and within experimental situations; and of the larger role of praxis and perception through such technologies." (1991, p. 99)

Significantly, in this paradigm, technology is no longer merely applied science; it takes a leading role in the process of doing science. The instruments, from microscopes to

telescopes, become "readable technologies" (p. 106); undeniably, they alter and augment perception. The very design of scientific instruments for sensing and generating data mediates and influences research outcomes. For example, when gathering wave lengths from telescopes, scientists map color onto black and white images, a process that affects the perception and ultimately, interpretation of the image. Of this, Idhe writes, "In false-color projects, the deliberate introduction of color makes visible that which ordinarily would be either invisible or too lightly contrasted to notice" (p. 74). Similarly, whether researchers observe through telescopes or microscopes, they expand upon the eye-brain system, employing technologies that mediate direct experience, observation, and empirical findings. Ken Goldberg, in *The Robot in the Garden* (2001), describes the study of knowledge acquired at a distance as "tele-epistemology."

Whether technologies are used in science or entertainment, from IMAX cinema to the CAVE™ to digital domes, technologies affect perception and interpretation (Grau, 2008). Science participates in technological embodiments as part of its process of doing science, from picking up rocks on Mars to manipulating nanobots in the human body. As we expand our distance from direct experience, scientific realism cannot avoid the epistemological questions raised by technologically mediated observations.

Computational science provides yet another extension and mediation of how we perceive and understand our universe, in some ways more extreme than those developed historically. Supercomputers provide a digital laboratory of a different kind than the tele-technologies Ken Goldberg describes. Computational science could be metaphorically compared to these other tele-sciences; however, there is a fundamental difference. The digital laboratory of computational science is not directly coupled to human senses in the same way as a scanning microscope is coupled to the eyes or remote robots are coupled to the hands. Computational science instead couples supercomputers with cognitive

constructs of data that has been derived instrumentally, using our symbiotic brains. This is

my own, enriched yet differentiated way of understanding the old concept of computer

science as a symbiosis between mind and computer (Licklider, 1960; Dyson, 1997). As a

result of this dynamic, computational science has an epistemology all its own, what I will

call a digi-epistemology, which is manifested through its method of creating simulations,

models of natural phenomenon, that are defined in terms of mathematical hypotheses.

Significantly, digi-epistemology's first-order, embodied experience is provided by

digital visualization, which realizes scientific theory through manifesting it in a sensory

form. Like other tele-technologies, visaphors give us a "glimpse" into a world that is

impossible to experience otherwise. Yet the source can only claim to be purely digital; it is

not directly coupled to any natural phenomenon. By claiming for digital visualization its

own epistemology with regard to computational science, we gain a new field of research

opportunity for understanding how we derive knowledge from this purely digital

foundation. Visaphoric art forms provide an essential domain of inquiry for this research.

The Contingency of Data and Construction of Scientific "Truth"

Our visually-oriented scientific culture in the West has come of age during a digital

revolution where images and numbers merge. One would think that this merger would

silence critics of visualization's value to scientific discovery. Yet, that tension continues to

impact the theory, practice, and funding opportunities for scientific visualization and its

artists. Although the mathematical models that are represented in scientific visualization

intended for expert audiences have enabled significant predictive powers, some scientific

circles continue to find such methodology too speculative. Scientists do not yet understand

fully why mathematics works to predict phenomena, other than to claim that it is the

primary tool for discovering self-evident "reality." Dr. Larry Smarr, astrophysicist, says that we must take mathematics on "faith" (personal communication, 2001). In practice, computational science reveals that the supercomputer mathematical models are not self-evident definitive results; rather, they are heuristic processes for seeking and best fitting a problem solution.

Within data-viz theory, many positions can be generalized into two distinct polarities. On the one hand, nature in all her glory waits to be discovered with unambiguous scientific precision. The mathematicians, scientists, and philosophers of logical positivism in the twentieth century promoted literal language and mathematics as being the most relevant and important tools for science. The underlying, deep assumption of logical positivism is that mathematics and literal language can describe reality. At the opposite end of this philosophical position prevails the central idea that reality itself is always mediated and the result of a mental model is that human beings construct reality through perception, language, culture, and other belief systems. (I have already discussed this division at length in Chapter 3).

Historicizing the use of images within the scientific process has led many modern philosophers of science—their humanist orientation being key--to recognize and even express awe at the power of the scientific image (Latour, 1979; Lynch and Woolgar, 1990). They have gone so far as to claim that our scientific culture is a "visual" culture, historically as well as today. Revisionist thinkers in the history and philosophy of science such as Thomas Kuhn (1962) and Mary Hesse (1966, 1980) have challenged traditional scientific accounts of progress that are grounded in logical-positivist tradition. They have examined the subculture and discourse of science to reveal metaphorical and paradigmatic shifts that exceed the bounds of objectivity but enable creativity. As a result, many contemporary philosophers of science—if not the majority of scientists themselves—

135

recognize that observation is not neutral (it is shaped by an observer's emotion,

perspective, and conditions) and that science and technology develop not in a linear

progression (from one great scientist's revolutionary discovery to the next), but through a

much larger and more complex sociological process, in which meanings are as negotiable

as methods (Latour and Woolgar, 1979; Latour 1987; Headley, 1997; Van Bendegem,

2000).

For example, when we examine what broader set of conditions helped to produce

visaphoric maps of the universe, we uncover a surprising past. Many cosmology

simulation codes are derived from nuclear physics research that began during World War
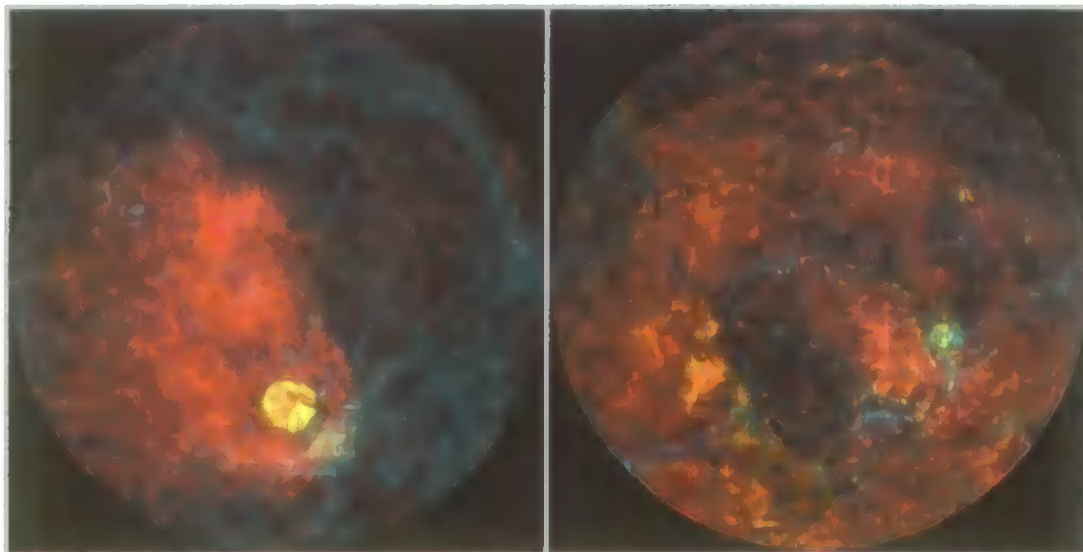
Figure 20. First star goes supernova: On the left, a first star in the universe forming within a red-orange
nursery of hot gas; on the right, after living a short life, the star goes supernova, bursting in a
complementary red-gold pinwheel of debris and dust particulates.

II. John von Neumann and Norbert Wiener invented most of the foundational

mathematical methods to calculate nuclear reactions using modern computers (Heims,

1987). The extension of this work in computational science led to many modern

astrophysical simulations, such as the formation of the first star, its eventual supernova,

and resulting galaxy formation shown in *The Black Holes Project* (see Practicum

Compilation DVD 1: General Visaphor Sequences, Star-Galaxy Formation *Black Holes*

Project, 1.3.1 and 1.3.2) and (Figure 20).

Richard Rorty's neopragmatist position—articulated in *Philosophy and the Mirror*

of Nature (1979)--establishes a means for contemplating the contingency of our ontology:

a growing sense that philosophy cannot establish a ground of truth, but that our sense of

truth is fundamentally constructed, mediated. From the perspective of our species-level

intelligence, Rorty reasons that we are entrapped by the very biologically and culturally

contingent beliefs and values within which we operate: our milieu, our environment.

Rorty's stance is a response to traditional Western philosophy's historical goal of

attempting to resolve our "reality" with our experience. As we have approached

modernity, our tendency is to no longer find a separation between body and mind,

collective and individual, environment and phenomenon. This view is now found

throughout contemporary thought, in the humanities via metaphor theorists such as Lakoff

and in the sciences via cognitive scientists such as Varela. Thomas Kuhn has been

particularly influential in arguing for how our networks of assumptions provide a basis for

many of our basic scientific theories. For example, the anti-foundational turn we find in

Rorty may be seen as derived from the continuing cultural impact of Einstein's theory of

special relativity (which asserts that time and space are perceived differently by observers

in different states of motion). Thus, scientific certitude is challenged not only by later

discoveries that revise our understanding of the natural universe—its nature and principles

of operation—but also by the socially-constructed nature of knowledge, including

scientific knowledge; the processes by which it is constructed and communicated; and their

cultural, political, and economic determinants (Heims, 1987; Ihde, 1991; Buchwald, 1996;

Dubow, 2000).

In computational science, data and the knowledge produced from it may be considered even more removed, and therefore contingent, from that which is instrumentally derived. Scientists who employ computational methods attempt to validate their numerical models by testing the model for known, internal inconsistencies or computational defects. Validation refers to checking the computational code for obvious errors, but it cannot validate the truth value of the scientific model. However, as they work, these scientists continue to improve their computational models in order to produce better results that can predict natural phenomena (Oreskes, Shrader-Frechette, and Belitz, 1994). While numerical models can never be proven to be true by logic, they can be confirmed with other kinds of data. In *Science*, Oreskes, Shrader-Frechette, and Belitz state, "Numerical models are a form of highly complex hypothesis. Confirmation theory requires us to support numerical simulation results with other kinds of scientific observations and to realize that verification is impossible" (p. 642). The authors explain that the numerical model cannot be verified or validated, only confirmed: "What we call data are inference-laden signifiers of natural phenomena to which we have incomplete access" (p. 642).

Why do computational scientists continue to improve numerical models even though they cannot be formally validated or verified? Numerical models have succeeded in studying natural phenomenon; they provide a new scientific methodology to address the complexity of nature. These models help us to discover, explore, and learn in combination with other types of observations. Numerical models provide enough accuracy and understanding of natural processes to contribute knowledge that is inaccessible in either time or space. For example, in astrophysics, numerical modeling augments scientific telescope observation and provides another tool to further analyze, understand, and support observational data from telescopes (Kaufmann and Smarr, 1993; Reed et al., 2005). Computational numerical modeling provides a heuristic approach: to discover and learn by

numerical testing through trying out numerous solutions. This heuristic approach provides experience-driven knowledge, which is very close to the exploratory research-in-practice approach that artists use, even if most of us do not employ numerical methods to develop our models.

However, even those made uncomfortable with such computational science's method at a remove must acknowledge that instrumental approaches provide no compensating certitude. The history of the interpretation of the Milky Way is replete with social misconstructions, paradigm-shifting egos, and technology-mediated errors (Jaki, 1990). Even today's advanced telescopes and satellites provide incomplete data. Our best telescopic mappings of the stars nearest to our sun include expansive ranges of potential error as a function of technological limitations or statistical approximations.

My own view of visaphors complements a philosophy of scientific knowledge as constructed and contingent. Granted, visaphors map from an empirical, objective source domain, or as close to such a domain as we can achieve, given that the data obtained and the models derived from it are based on active theories. Yet, not all of the data is mapped. Just as a storyteller may select some incidents to recount and others to elide, scientific visualization artists and the scientists with whom they collaborate make choices about what data will be modeled and mapped and what will not (as I have already described in Chapter 2). This selective modeling and mapping is not arbitrary. The selection of some data points and the imposed or understood relationship to others is a process of active meaning-making; it performs a semantic function. Perhaps even more importantly for the purposes of this argument, as is the case with any metaphorical construct, an artist expressing visaphors has the choice to represent modeled data within a range of conventions, from those that may be taken as expected and literal to those that appear novel and figurative (as I have discussed in Chapter 3). Further, when visaphors map data

139

models to a representation, both artist and audience draw upon a complex source domain for constructing and interpreting it, one that includes not only the culture of science, but also whole concept networks derived from intellectual and popular cultures. The specific characteristics used to visually represent data--such as color, shape, scale, and movement—thus perform a semiotic function. They don't just inform; they signify.

How visaphors shape our sense of scientifically-authorized reality, and how much, is of vital importance. The popularity of data-viz and its public presentation have increased dramatically since the advance of computer graphics, supercomputing, and the Internet. Millions of people flock to view visaphors that enhance scientific narratives on television, in museums, in planetariums, and online; they also happen across them all the time without necessarily realizing it in journalistic as well as educational media. Because visaphors carry the "weight of scientific accuracy," most people believe that visaphors represent the "true" view of reality. However, data is not sacred, and visaphors are approximation models, not reality. We must never forget that the map is not the territory-- there are always alternate ways of viewing the universe. In the process of creating consistency and organizing information, in the process of securing scientific authority, we tend to abandon the creative possibilities, and the promise of new intellectual discovery, that could be enabled by scientific visualization.

An Alternative Philosophy of Science: The Evolution of Consciousness

To understand how computational scientific visualization and its visaphors differ from other forms of visual communication, we must understand something about the symbolic economy of science—not the matter of science, but the construction of science as an epistemological domain, a construction that can vary based on its assumptions about the

140

nature of existence. In my data-driven art, I have sought to represent not isolated phenomena, but the autopoetic nature of our world and its surrounding universe. As early as 1966, in "Behaviorist Art and the Cybernetic Vision," visionary Roy Ascott anticipated such a transformative, self-organizing art in describing what I characterize as his cybernetic turn from modernism (Ascott, 2001). In a prophetic embrace of cybernetics and environmental technology, Ascott predicts a new technology-charged environment in which an artist may "come to terms with his world, shape it and develop it by understanding its underlying cybernetic characteristics" (p. 101).

My own understanding of visaphors' special aesthetic has evolved through my engagement with an ambitious but minor intellectual tradition in the philosophy of science that arose in the latter half of the twentieth century, one that has constructed an account of how evolution, complexity, and consciousness relate to one another and change together over time. The philosophers of this tradition are predisposed to view the natural world as made up autopoetic systems that emerge from the convergence of individual elements to form the one, and then multiply into the many. Unity becomes diversity; diversity becomes unity. For these thinkers, this emergent pattern of matter- and life-shaping forces runs right through evolution. From energy-bound atoms to living organisms, isolated elements assemble into new order.

Paleontologist and Jesuit priest Pierre Tielhard De Chardin was the first to articulate a belief in the evolution of consciousness from a scientific point of view. His major work, *The Phenomenon of Man*, was published posthumously to popular success (first in French in 1955, and four years later in English translation). De Chardin's argument figures universal evolution as a single process that drives toward increasing levels of complexity and consciousness. Throughout his book, De Chardin uses the term "consciousness" in its widest sense: "From the most rudimentary forms of interior

141

perception imaginable to the human phenomenon of reflective thought" (1959, p. 57). De Chardin suggests that from atoms to the large-scale universe and back down to the infinitesimally small, "from this primitive and essentially elastic quantum, all the rest has emerged" (p. 72). In essence, the universe is in a continual process of remaking itself. Its increasing organizational complexity reveals a more complex interior "within"—in the broadest sense, a consciousness. From each disciplinary vantage point, and through external observation, De Chardin finds the universe reveals an evolving complex system, a unified totality with boundless energy--as if it were going somewhere. De Chardin's description of this all-pervasive universal tendency toward "complexification" (p. 48) anticipates Maturana and Varela's autopoesis: "Each element of the cosmos is positively woven from all the others: from beneath itself by the mysterious phenomenon of 'composition,' which makes it subsistent through the apex of an organized whole; and from above through the influence of unities of a higher order which incorporate and dominate it for their own ends" (p. 44).

For De Chardin, the universe has a double aspect: the within, consciousness, co-evolves with the without, external matter. On this point, he writes, "things have their *within*; their reserve, one might say; and this appears in definite *qualitative* or *quantitative* connections with the developments that science recognizes in the cosmic energy" (p. 54). In the universe's evolutionary processes, inanimate particles aggregate into life components, which in turn aggregate and ramify through differentiating layers of spatial-temporal scales of experience (what he calls "levels" or "spheres"). Biological processes lead to the incredible diversity of species and phyla and eventually to humanity and culture. De Chardin writes, "On the one hand the individual unit is lost in number, on the other it is absorbed into the collectivity, and yet in a third direction it stretches out in becoming. This dramatic and perpetual opposition between the one born of the many and

142

the many constantly being born of the one runs by through evolution" (p. 111). This continual interaction between multiplicity and unity seems to move evolution forward through a "groping" mechanism (p. 110). In *The Tree of Life: the Biological Roots of Understanding*, Maturana and Varela expose this tendency in what they define as "natural drift" in which each organism and its environment undergo a continual transformation in relation to one another (1987, p. 100).

How does this happen? De Chardin believes the within is constituted by inanimate component particles that evolve more complex and emergent properties, ultimately into human thought, a critical transformation. "Consciousness reveals itself," he writes, "as a cosmic property of variable size subject to a global transformation" (1959, p. 59). This moment of transformation is akin to phase transitions between different states of matter, such as the instant when a pot of heated water reaches the boiling point, its agitated molecules releasing roiling bubbles and steam vapor that suddenly become visible to the eye. The rise of consciousness as human thought is for De Chardin a critical state of transition. Astrophysicists studying black holes also see this critical point of transition, referring to it as a "singularity": the point of no return for the gravitational pull around a black hole. De Chardin believed that the transition to human thought was a critical point in the history of the evolution of life: "But in depth, a great revolution had taken place: consciousness was now leaping and boiling in space of super-sensory relationships and representations; and simultaneously consciousness was capable of perceiving itself in the concentrated simplicity of its faculties" (1959, pp. 168-169). This process may be taken one step further. Ultimately, through scientific thought and investigation, "evolution at last becomes conscious of itself" (p. 20). De Chardin's evolutionary view anticipates Margulis's stance on the symbiotic brain evolution of higher consciousness (Margulis and Sagan, 1986, p. 22). Significantly, theorists of this tradition believe that in some twist or

evolutionary inversion, the human collective self-reflects upon its own evolutionary processes.

Exampled in the sciences, De Chardin would say that physicists study the without of material matter, such as the formation of galaxies or the existence of gravitational pull in the universe. The physicist focuses only on what can be observed, measured, or modeled. Science's assumed restriction of the phenomenon of consciousness to the higher forms of life has long served as a rationale for eliminating it from models of the universe (1959, p. 55). In my collaborative experience with scientists, I have likewise found that science asks simple questions and constrains experiments to the measurable materiality of the without. As an artist, my goal is to explore and expose the within and make this invisible within visible and accessible to others. Visaphoric art exposes the attenuated extension of our evolutionary processes and their autopoetic systems (Chapter 5 will further explore this aspect of visaphoric art).

Although De Chardin does not play a central role in mainstream evolutionary theory, he cannot be entirely discounted. He has influenced important contemporary and later thinkers and anticipated scientific themes and technologies, such as complexity theory and the globally conscious connectedness of the Internet. During his time, there was little agreement among biologists as to the axis of evolution or the line between animal instincts and human thought (1959, p. 164). What is agreed today is that life-forms increase in neural complexity, when all of life is understood as a cognitive system (Maturana and Varela, 1987). This assumption is central to De Chardin's thought: "Whatever instance we may think of, we may be sure that every time a richer and better organized structure will correspond to the more developed consciousness" (1959, p. 60). For him, "Life is a major transition in this evolution. Life marks a major threshold in the rise of consciousness"

(1959, p. 153). The arrival of modern, thinking *homo sapiens* marks yet another threshold in this on-going evolution of consciousness.

Most contemporary scientists would probably view De Chardin's concept of the "within" with skepticism. I view it as prophetic, scientific poetry, a description that resonates with scientific themes from Lynn Margulis (1986), Francisco Varela (1997) and Stuart Kauffman (2008). To me, as an artist, the "within" represents those invisible processes that push toward coherence, that begin to emerge a unifying property. This may not be clearly observable, yet they can be revealed through art. What is more, I believe De Chardin captures the essence of how we personally experience progression toward the future as we humans ride the arrow of time. We must give him credit for sharing his personal, embodied experience of scientific knowledge. Although one cannot deny that De Chardin's poetic vision impinges upon his philosophy and colors his scientific approach, many of his ideas resonate with modern scientific thought in a variety of science domains, including cognitive science.

When De Chardin describes ascending neural complexity in evolution, he invokes a well-documented biological phenomenon: the aggregation of colonies of cells and the ascending complexity of the chain of life that reflects complex, self-organizing, self-sustaining bio-organisms and bio-organic systems. Simple bio-organisms differentiate through more complex and added mechanisms, and organize into more complexity. The richer and more complex the structure, the more advanced the consciousness. Greater complexity of the organism yields more advanced mechanisms that in turn contribute to the whole system. A defining characteristic of more complex bio-organisms is that of "groping." Groping is directed chance, an interaction between organism and environment. De Chardin lauded pure scientific research, seeing it as a sophisticated extension of this "groping" mechanism. What is striking is that both scientific and artistic inquiry

145

incorporate this "groping" experimentation. The artistic process is one of essentially

playful exploration, where "trying all" is not as constrained as the funding-constrained

process of trial and error in the research avenues of science.

De Chardin, in his own groping, was enacting a process of scientific discovery,

even though his process was more akin to that of Descartes, in the tradition of rationalism

rather than empiricism. To be fair, De Chardin would have disagreed with such a

characterization. He argued that his treatise was founded on scientific "seeing"

(experimental observation), rather than philosophical ruminations. "To harmonize objects

in time and space, without presuming to determine the conditions that can roll their deepest

being: to establish an experimental chain of succession in nature, not a union of

'ontological' causality; to see, in other words, and not to explain" (1959, p. 58). De

Chardin's assertion that he is describing what he finds externally rather than arriving at his

conclusions internally, and that he is not addressing reasons for the phenomena he

describes but merely reporting them, does seem to secularize his approach and make it

complementary to modern scientific methodology. In fact, his approach was too scientific

and secular for the Vatican to allow him to publish during his lifetime. His desire to see,

and not to explain, captures my own intent when I collaboratively create visuals to be

experienced and embodied. The embodied experience of scientific visualization stimulates

metaphorical knowledge, and may in turn both reflect and contribute to our evolving self-

consciousness. The visualizations I produce in collaboration with others are the artifacts of

our collective, cognitive culture.

Other scientists hold views that are in sympathy with De Chardin's. His sense of

the universe evolving toward greater consciousness is also found in James Lovelock's Gaia

hypothesis (Barlow, 1991) and the natural theology of Freeman J. Dyson in *Infinite in All*

Directions (1988). Dyson, a physicist, proposes that consciousness is expanding across the

146

universe in alternative forms in addition to human beings. Since De Chardin's "within" reveals itself through increased complexity, especially relevant in life forms, his views find complements in the cooperative, symbiotic evolution championed by Lynn Margulis and the autopoesis described by Francisco Varela.

To move this tradition forward in time to the near present, I turn to Varela. Like De Chardin, Varela studies possibilities for the transformation of human consciousness (Varela, Thompson and Rosch, 1991, p. XVI), but with a Buddhist orientation (rather than a Catholic one) and from a contemporary biological and cognitive perspective. Varela's view is narrower, centering on the evolution of the human mind, rather than the evolution of the human species as a whole. In *The Embodied Mind: Cognitive Science and Human Experience* (1991), Varela and his colleagues focus on individual cognitive experience as a phenomenon that emerges from complex organizational processes. Varela points out how self-organization defines a layering and emergence of higher-order properties in complex organisms. Elemental components come together, forming what can be perceived as a complex whole. Together with Humberto R. Maturana in *Autopoeisis and Cognition: The Realization of the Living*, Varela names this process "autopoesis" (1980). Autopoesis defines a spontaneous, dynamic, self-organizing, self-producing process that yields an autonomous, self-maintaining unity. For example, a cell or a corporation is autopoetic.

In *The Tree of Knowledge: the Biological Roots of Human Understanding* (1987) Varela and Maturana refine and expand this definition, echoing De Chardin's critical singularity when the conditions were right for life to burst over the planet earth: "All the available evidence leads us to believe that once conditions were ripe for the origin of living systems, they originated many times; that is, many autopoetic unities with many structural variants emerged in many places on the Earth over a period of perhaps many millions of years" (pp. 50-51). "It is possible," Varela writes, "then, to see the notion of a heap or pile

147

as a metaphor for what we would now call a self-organizing process" (Varela, Thompson, and Rosch, 1991, p. 98) The collective experience of society and its culture is more than a heap or a pile; it is autopoetic. Autopoetic complexity circles in on itself. At each new threshold, a distinctive "within" ascends as this consciousness reveals its own evolution through its historical trails and self-reflective collective. This dialogue with itself is part of the evolving consciousness of the entire system. Varela contends that individual components interact in a bidirectional way with their environments. Individuals affect their environmental systems, shaping them as much as these environments shape the individuals of which they are composed. Thus, he rejects the metaphor of the mind as a passive, symbolic processing unit, or computer (Varela, Thompson, and Rosch, 1991, pp. 7-9, pp. 40-42). Individual self-reflection is not solipsistic; it participates in a dynamic of collective construction and response (p. 27, p. 39).

Varela and Maturana distinguish this evolutionary process from allopoiesis: the process by which self-maintaining unities also produce something other than themselves. From individual cells that produce substances of benefit to their host organism to human social collaborations, such as Renaissance Teams, allopoietic unities not only promote cooperation, but also resist excessive individualism and compartmentalization—limiting tendencies cultural theorist Roy Ascott has warned against in the *Telematic Embrace: Visonary Theories of Art, Technology, and Consciousness* (2003) in promoting "art based in scientific metaphor" (p. 341). Indeed, by considering the range of human cultural production, including science as well as the arts and humanities, we gain the potential for a more relevant, modern aesthetic as well as a more informed, self-conscious scientific practice.

Another contemporary scientist who works in this new evolutionary tradition is Lynn Margulis. In *Microcosmos: Four Billion Years of Microbial Evolution* (1986),

148

Margulis and Dorion Sagan find power and promise in the collective and the cooperative, rather than the individual and the competitive. Like De Chardin she conceives of autopoetic systems as the basis for all known life; like Varela, she understands highly complex, autopoetic systems as evolving toward consciousness, as in her theory of the symbiotic brain. Margulis claims it is through symbiosis, and beneficial coexistence, that life has evolved (Margulis and Sagan, 1986, p. 91). She argues against the idea of "survival of the fittest," like many who recognize that Darwin meant survival of the "fecund" (and not the cutthroat competitive slaughterhouse often characterized in our popular science infotainment media, such as Animal Planet). She points out that emergent life required cooperation to prevent extinction, giving the example of the single organic cell, which is an autopoetic system that has been recombined from bacterial predecessors that learned how to cooperate. Early bacteria coevolved into complex, self-sustaining colonies, recombining as they did so like hybrid mythical creatures: unicorns and griffons, mermaids and centaurs. For Margulis, the complex human brain demonstrates an evolutionary outcome of symbiotic bacterial life, and human thought is a superorganismic outgrowth of the biosphere. The symbiotic brain is more than the human brain; it is a collective phenomenon that continuously stretches from its bacterial genesis forward through modern, technological advances (Margulis and Sagan, 1986, pp. 151-152). Her grand view is that of an evolving cosmos on a vast scale, a supercosm, where cooperation is as important, and perhaps ultimately more important, than competition.

As is the case with many other modern eco- and post-human thinkers, Margulis does not give special significance to human beings; they do not serve as a pinnacle of the evolutionary rise. She grants that the last 50,000 years has uniquely produced what we might think of as culture: the creation of artifacts, narratives, and ritual--a marked achievement of *homo sapiens*. However in terms of biological evolution, she places

humans squarely in the ape phyla; they are not an extra-natural phenomenon. Margulis

believes that humans are egotistical about their place in the universe. On this, she writes,

"Our powers of intelligence and technology do not belong specifically to us but to all of

life. Intelligence and technology, incubated by humankind, are really the property of the

microcosm. They may well survive our species in forms of the future that lie beyond our

limited imaginations" (Margulis and Sagan, 1986, p. 24). Indeed, humanity's intellectual

egotism led Renaissance societies to resist revolutionary Copernican thought that the earth

was not the center of the cosmos, and continues to limit present-day constructions of the

real, which cannot help but continue to be culturally mediated, even though they are

understood as objectively derived, or scientific. My Renaissance Team approach

recognizes the value of the human collective and positions our collaborative work in the

larger social network of this ideological ecosystem.

Through her own biological lens, Margulis views evolution as a continuing process

without any particular summit or end. It is a potentially infinite process, determined by the

continual replication and survival of the microbial world. The microbial world has existed

and survived through millions of years on this planet, in the environment and as

constructed in various species, including thousands of years within and as part of human

life forms. Like Freeman Dyson, Margulis believes consciousness is spreading through the

universe in microbial proliferation; evolution will probably leave humans behind. For

Margulis, humans and our works, including technology, are merely an extension of

microbial evolution. Our development of technology is what Margulis would refer to as a

"coevolution." The universe, biologically speaking, re-expresses its functionality through

various forms, and technology is one of them. Whether the function is expressed through

the co-evolution of pinchers on a Dungeness crab or the robotic pinchers on autonomous

vehicles, the whipping motility in a paramecium or the nuclear-powered propellers of a

150

submarine, the universe evolves and recapitulates. For example, the same evolutionary motility expressed in spirochetes 3,000 million years ago is expressed through space shuttles today. Bacterial communication and transmission is reflected in human perceptual acceleration such as speech and extended through radio and modern communication systems.

Just as spirochetes may have formed microtubules that eventually formed the symbiotic, human brain, Margulis wonders whether "groups of humans, sedentary and packed together in communities, cities, and webs of electromagnetic communication, are already beginning to form a network as far beyond thought as thought is from the concerted swimming of spirochetes" (Margulis and Sagan, 1986, p. 153). Both Margulis and De Chardin anticipated global communication as an extension of evolutionary processes. We have few conceptual metaphors to help us grasp the outcomes of such networked social and electronic communication collectives. As a result, Margulis speculates, "We stand no more chance of being aware of the totality of such a form of group organization than do the individual components of brain cells--microtubules, the putative remnants of spirochetes--understand their own mission in our human consciousness" ((Margulis and Sagan, 1986, p. 153).

A crucial mission of the visaphor arts, then, is to produce novel ways for us to contemplate not the impact of technology on society—as the problem is so often phrased— but the evolution of our technology as a cybernetic extension of ourselves, inseparable from our own becoming. Visaphors provide us with a medium for evolving and acknowledging the evolution of humanity--not as a life form separate from a natural order or superior to it, but as a species whose collectively embodied mind has been formed through planetary forces and, as we stretch farther beyond our earthly bounds, perhaps cosmic forces as well.

I find Margulis's argument for a continuity of human evolution from primeval capacities through human resourcefulness and into technological innovation compelling. Having felt myself a part of this extraordinary bio-computer-human process, I have wanted to contribute to the evolution of culture and its solutions of large-scale problems in the world. From very early on, it was apparent to me that interdisciplinary teams would be a better approach than as a single artist. This approach is better because it recombines intellectual ideas and disciplinary expertise. In scientific visualization, a diversity of skills is necessary to address visualization across a variety of scientific domains. In managing such collaborations, I sometimes feel like a conductor of an orchestra. Each position plays a part, providing a unique contribution to the whole piece. I direct the orchestra, but each player plays a crucial role in the symphony. Cooperation and collaboration are key. This process of collecting, re-combining, and recirculating is a pattern that emerges from the universe: the recombination of DNA, of matter, of ideas permeates evolutionary processes (Maturana and Varela, 1987).

An impediment to our cybernetic evolution is the separation we continue to propagate between art and science. This systemic segregation can be felt from funding mechanisms to university reward systems. The divide has not always been so extreme. Over the course of Western civilization, the divergence and convergence of art and science has been in flux: an evolving, autopoetic pattern of diversity and unity. Both art and science provide valuable frameworks for apprehending, revealing, exploring, and visualizing this stuff of the universe. The advent of computer graphics has enabled new means of image making, icon making, and storytelling. It provides a new cultural ground for the convergence of art and science, yielding a psychologically and socially powerful instrument. The cybernetic art of scientific visualization satisfies our tribal need for myth and creates mythic futures (Ascott, 2001, p. 160). This primal human need may have been

152

set by our microcosmic beginnings, a need to capture that grand vision of the one being a part of the many--a part of something much bigger than oneself--the need to express and experience creation stories that are validated by our "high priests" of science. I see myself as participating in the synergy and flow of a universe in motion, re-enacting its flux on biological and technological scales. The telematic art of scientific visualization is not so much the process of revealing existing physical reality through data as it is the process of providing a visual glimpse into the internal, evolutionary processes that express themselves through the creation and consumption of cyberceptive perspectives.

Visaphors provide us with emergent metaphors that extend our symbiotic brains into cybernetic communion. Through our use of digital devices, we extend our perceptions, imaginations, connections. The human, scientific brain attempts to capture nature through mathematical metaphors generated and recycled into digital symbols, terabytes of numerical, symbolic data that form a metaphorical layer through the medium of computer graphics. Visualization artists re-metaphorize these mathematical symbols into image-based, sensual renditions that humans can re-consume and re-process through their experiential, embodied minds. We stream these visuals electronically, chemically, and digitally over computers and networks to projected display devices that mimic bio-visual processing in nature. Digital pixels are rendered and fed back to other humans in colorful, light-filled, immersive environments that satisfy sensual as well as basic, tribal instincts. Our transmission of metaphor through digital devices generates a collective consciousness, expanding our scientific and larger, cultural metaphorical systems. Scientific visualizations and related narratives provide the story of our genesis and our evolution. They bootstrap our awareness and feed our imaginations. They provide an alternative conscious experience of the universe around us, helping us not to fix a reality so

153

much as they help us to realize the maya, or deluding power, of our existence, especially its dynamicism and interdependence, its impermanence and change.

As a telematic visualization artist, I participate in life's strategy of capturing and visually reflecting back on itself. The process of making the invisible visible is what "life is doing." The art of scientific visualization is another grand, self-iterative loop in nature's strategy to "see" itself. Like an Escher painting, the evolving universe iteratively mirrors itself from our bacterial ancestors through humans through technology and back again into the "moist media" (Ascott, 2001, pp. 363-366) of our evolving culture. Ascott envisions this self-evident reframing of consciousness through art in his manifesto. "Art," he writes, "is a form of world building, of mind construction, of self-creation, whether through digital programming, genetic code, articulation of the body, imaging, simulation, or visual construction. Art is the search for new language, new metaphors, new ways of constructing reality, and for the means of redefining ourselves" (p. 365). What we construct is what we can understand through our limited perspective, perception, conception, and interpretation with our collective, symbiotic brain. But the grand evolutionary process, the "way," has been marching on through multitudes of overlapping autopoetic systems and recapitulating through metaphorical thinking within humans.

Through the techno-scientific, visually embodied experiences I help to create within digital domes, museums, television, and the Internet, I participate in the creation of an experiential, cultural cyber-reality imbued with the persistence of myth. Visaphors are not merely visual rhetorical devises, nor are they confined in their importance to scientific communications. As tribal signs, they serve our needs for understanding and placing ourselves within a framework of existence. They are the shadows of human engagement with the imagined actual that we sketch on our new CAVE™ walls; the kaleidoscopic windows opening out onto creation that illuminate the digital cathedrals of our science

museums; the constellated domes beneath which we invent new stories, prophecies, and dreams. In our cosmic scientific visualization productions, such as *The Black Holes Project*, we take our audiences beyond the speed of light to worlds they can only experience through a new, collective imaginary. We generate new tribal artifacts of our shared, cognitive culture.

Why, logical positivists might argue, is the making of visaphors a valid epistemological act? Their data is contingent upon layers of assumptions, the supercomputers used to create them are inadequate for computing closed systems, and our very interpretation perceptually of what we find is relative to our species-level intelligence. As Rorty, Hofstadter, and so many others have argued, we cannot create and we cannot consume visaphors from without the human perspective: we are locked within it. Visualizations, like other types of data-driven imagery, tell the tales of their practical use and informing politics, of cultural assumptions and methods of communicating them. They are useful not because they give us a concrete view of absolute truth / reality; they are useful and pragmatic because of their consistency in helping us to navigate the world, within the communities and systems of beliefs within which we operate. They help us to make sense of the world by serving as metaphorical props, helping us to reach much larger concepts and categories of understanding, and giving us a creative medium for expressing new ideas. Like Shiva's dreams that create the world, visaphors materialize that which we too are dreaming.

Chapter 5: Scientific Semiotics: Mapping Matter, Making Meaning, Emerging Myth

The forms visaphors take are largely determined by scientific culture and its informing dominant paradigms (which continue to be those of the Western Enlightenment). Through implication and juxtaposition, they impact our understanding of everyday reality, much as linguistic metaphors have been demonstrated to do. We benefit from recognizing that data-viz is a culturally contingent process and that the information it communicates is further filtered through our technological media. In preceding chapters, I have been arguing that the process of data-viz is metaphorical in nature, despite its depending on a process that maps hard data to "realistic" representations of that data. In this chapter, I will explain to what degree and in what ways scientific visualization artists are free to aestheticize the visualizations they help to create.

Communicating Partial Truths

The visual models we create help us understand one domain of information in terms of another, but these are not one-to-one mappings. Information is edited or lost, and this provides us with aesthetic choices as well as ethical considerations. When planning a digital dome production, my choice as a visualization artist is to avoid showing the distracting error bars (Figure 21). To enhance the public's immersive experience, we often eliminate such didactic references. This is an aesthetic choice, not a deliberate intent to hide information. My artistic intent is to provide an embodied, aesthetic experience within the dome, to temporarily suspend disbelief and to cultivate what Joseph Nechvatal calls "immersive intelligence" (2001). Nechvatal argues that virtual, immersive art shifts

157

perception to a "peripheral mode" and increases situational awareness. Immersive displays
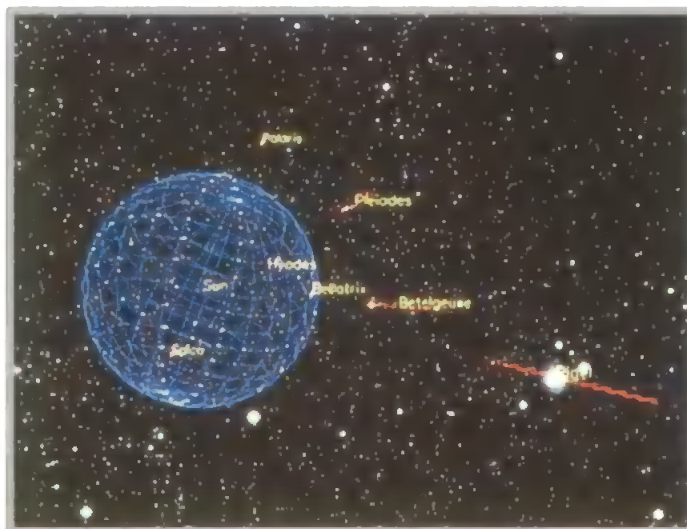
Figure 21. Error Bars: red bars indicate the range of approximation of distance between the stars and the sun. Three error bars correspond to three stars. The more distant the star is from the sun, the greater the error range.

such as the CAVE™ and digital domes may trigger and deepen a new virtual way of knowing visaphors that complements standard science communications (Davies, 2008). Virtual-reality artists have explored and documented some of these possibilities at *Consciousness Reframed*

conferences (Jones, 2000). Experiential technologies may help us to "humanize" the

scientific digi-epistemology of our modern, astrophysical maps. We use a different

strategy when we communicate with expert audiences, for whom the study of phenomena--

and not apparent, visceral experience of them--takes priority. When we created a

visualization of ocean flow within the Monterey Bay area of California intended for

oceanographers as the target audience, for example, we included didactic color legends

(Figure 22).

Despite my aesthetic choice to avoid visually distracting elements in popular

scientific visualizations, I remain concerned about lack of public awareness about the

nature of visaphoric elisions, especially in how this lack of awareness is symptomatic of a

broader ignorance of scientific methods, particularly those of computational science. Our

experience (such as in the surveys of the audience for *The Black Holes Project*) has shown

that most people will believe visaphors represent complete and literal fact, particularly

when these visualizations are displayed in documentary-style, mainstream media, which

tend to announce dramatized recreations of historical incidents but do not announce the editorial and creative nature of scientific modeling. A given target visaphor and its source data are embedded within concept networks that have inherent implications, beliefs, assumptions, and approximations that inform the artist's aesthetic decisions, including the adaptation of conventional data-viz representations such as glyphs. People learn how to "read" the image from their familiarity with the conceptual networks evoked. Although scientists are most comfortable discussing visaphors in terms of their data, the original information from which a visaphor is derived has actually been lost. It is not accessible to viewers, nor is its absence, in most cases, divulged to them. The concern here is that audiences who lack scientific media literacy can be misled or misinformed, whether the authors of scientific media mean them to be or not.

To demonstrate how information provided to lay audiences is manipulated and partial, I provide an example of an extraordinarily popular visualization we created at AVL. Figure 10 shows one of the first visualizations of the Internet, a visualization study of the NSF Net. In the upper portion of Figure 10, the partial boundary around the U.S. is skirted by a 300-foot virtual cliff made possible through 3D computer graphics; it drops into blackness without Mexico, Canada, or water. In the lower portion of Figure 10, a conventional earth map is used as a background for the backbone (white) and client networks. The color map indicates the flow of network traffic measured in millions of bytes. The source domain's concept network is, as usual, expressed only indirectly. Even technologically savvy viewers must learn to "read" the visual information this cyberspace map expresses, with its quantifiable color scale as a literal translation of data. A background in scientific discourse and information visualization certainly helps. The image also represents metaphors that developed in the technical community as a way of describing the internet in its early days. When the network was first being built,

159

technologists called the primary connections the "backbone." The white "backbone" is itself metaphorical, connoting human physical attributes: the thing that holds other things up and provides spinal connections (neural routes of "communication"). Not only may a lay audience perceive this visual metaphor as naturalized, but they may also be unaware of the non-present, source-data concept network, with the usual cultural biases, technological beliefs, geographical and mapping conventions, approximations, and even unintentional errors, misspelled words, and hand-corrected routing information. They will be unaware, too, that information has been suppressed, such as classified military networks, and excluded for convenience and readability, such as wireless satellite connections on mobile trucks and the entire evolving technology and political system we simplify into the term "digital data." The target visaphor's concept network likewise has its unrepresented assumptions, editing methods, geographical biases, and mapping conventions, which may not strike lay audiences. For instance, this cyberspace map ignores the United States' international neighbors and the global phenomenon the Internet has become.

Manipulating Signs

Visaphors are aids to understanding and the communication of it, but taking their relationship to informing data too literally undermines our creative possibilities. That being said, visaphors cannot be arbitrary; they have to work in a physical dimension or in a pragmatic sense; otherwise, people will not value or use them. Maps must enable us to navigate space, such that we get to where we want to go, and maps have to be consistent with our physical explorations. Thus, in expanding our sense of the creative potential for metaphors, we are, in effect, opening ourselves back up to alternative approaches to mapping the real. Alternative approaches to historical map-making may have been

160

abandoned for a number of reasons, including consistency. Our tendency of adhering to standardized systems of signification reflects the long-held desire for a universal language--especially in the modern era, a scientific one.

Even as linguistic translation is not mere transcription, the "art" of visualization involves a creative translation of data into visual representations; it is a more complex aesthetic decision-making process than mere mapping. This process of translation is similar to the manipulation of signs in semiotics (Hawkes, 1977; Bertin, 1983). Although in scientific visualization the visual metaphors, or icons, are directly bound to data, the artist makes choices about which symbolic icons, or visual metaphors, to use in representing that data, given the design constraints of computer-graphics technology and a range of symbolic conventions and their meanings that are familiar to the sciences and its internal and external audiences. Most of the time in the creation of visaphors, the data is large and complex. Thousands of spatial and temporal numbers are mapped. As the data to be mapped increases in complexity, so too do artists' choices of visual techniques for rendering that data.

In Chapter 2, I have already suggested how, through the creative invention of glyph-mapping, the artist can have a transformative influence on a visual model, as was the case with the IntelliBadge™ Project. I demonstrated there how artists can metaphorize data along a continuum from the literal and expected to the novel and surprising. To further build upon this idea, I want to also claim that the creative design of a novel glyph can be "transferrable." For example, my team and I adapted the flowing stream tube trajectories and bubbling iso-surfaces we developed to depict tornadic air motion and clouds to represent the flow and accumulation of water in Monterey Bay, California. The Monterey Bay visualization was funded by the NSF as part of the LOOKING project, which studied ocean current and temperature (Figure 22). This example reveals not only

161

that glyphs may be repurposed, but also repurposed across domains (here, from
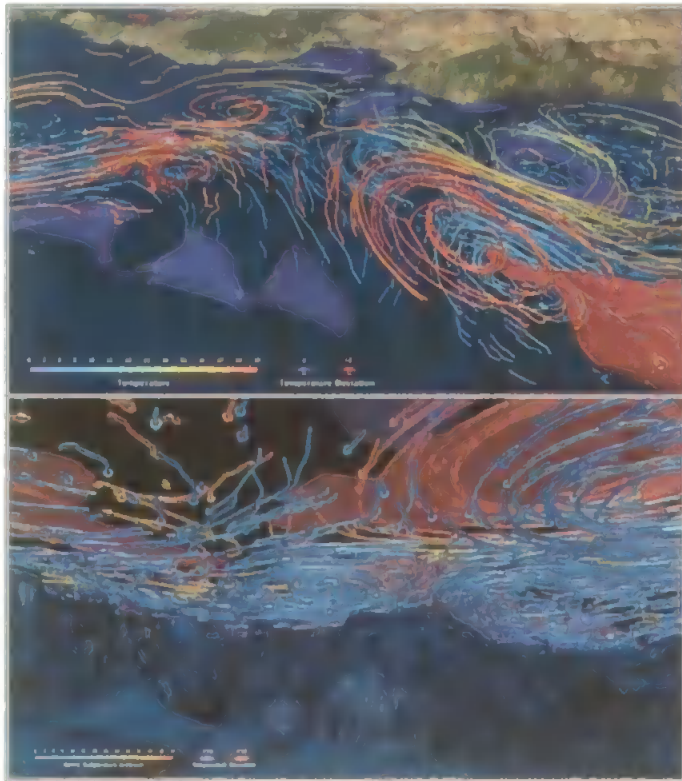
Figure 22. Monterey Bay ocean visaphor employs glyphs to show ocean flow with temperature mapped onto trajectory locations. Above is an aerial view; below is under the water. Gyphs can be transferred between scientific domains.

atmospheric science to oceanography). Compare Practicum Compilation DVD, 1: General Visaphor Sequences, Tornado and Ocean 1.2.1 and 1.2.3. The shared concepts from the source domain (flow, volume increase) enable the icon, which already has conventional associations with these concepts, to be used in two different target domains (air / vapor, water).

Mapping as Metaphor

Maps constitute one of the major sign systems that make up the visual language of science. Although modern maps originated in cartography, their methodology has informed scientific mapping processes and representations and been informed by them in turn. The ideas informing particularly influential forms of cartography for data-viz--thematic and graphical-statistical maps--predate the seventeenth century. They began to take visual form as European-style maps evolved from the eighteenth century forward. Maps increasingly included information icons and symbols to augment geological

162

information, often to the side, as abstracted, explanatory or superadded glosses, plotting phenomena such as demographic distribution.

Thematic maps failed to progress in the nineteenth and early twentieth centuries, since statistical mathematics displaced more visual approaches to conveying information (Akerman and Karrow, 2007). As a result, the full-blown, logical extension of cartographic information abstractions, thematic maps, arose at the same time as computer graphics under the influence of John Tukey (1962) and others like him. Thematic maps in cartography are especially closely related to scientific visualization in that a spatial (often a geospatial) context provides the basis for dependent data, whether statistical or scientific.

Visaphors are visual models made of selected, thematized, and ordered data: mappings, if not always maps. Like maps, visaphors are artifacts that reflect a culture's technological accomplishments in a given era. Both attempt to visualize, or illustrate, features of an external, material reality that have been determined using observational and extrapolative methods. Both play a role in educating and inspiring the public about the state of nature and how it may be reflected in human nature and society. As pre-computational data-driven visualizations, maps—their history and composition--can help us to understand some of the design operations and social functions of computer information visualizations.

Over the last thirty years in cartographic studies, the scholarly view of maps has become increasingly interdisciplinary and ideological. Map historians have come to understand that, in addition to their basic functionality as navigational aids and territorial determiners, maps communicate artistically and culturally. Many maps are considered works of fine art and decorative design. The decorative devices on maps often express more than their immediate purpose, tacitly communicating cultural values. Revisionist

cartographic history takes into account alternative maps and mapping methods, including

their propaganda politics and social impact (Harley, 2001; Akerman and Karrow, 2007).

Mapping is a metaphorizing process, one that is culturally determined. Today's

"universal" methods for spatially quantifying information have roots in Western, first-

world civilizations that are more dominant, not more intelligent, than Eastern, third-world

ones. Geographic maps are excellent examples of how literal, conventional visual

metaphors have developed into coherent and consistent systems. Their novel origins have

been lost over time due to their familiarity and cultural accommodation. In the history of

maps, texts written before the sixties show a cultural bias toward Western mapping

conventions (Bagrow and Skelton,1985; Black, 1997). For example, in *History of*

Cartography, Leo Bagrow reveals this bias in his criticism of "primitive" peoples' map

making abilities:

> Another prerequisite for map-making—an aptitude for drawing—is not present in
> all races, and where such a gift exists it does not necessarily include the ability to
> draw maps. It has been observed that, in general, races given to stylization of
> animal or human figures and to ornamentation of their utensils draw either no maps
> or very bad ones. Talent for drawing, though not dependent on a certain stage of
> development or degree of intelligence, can be gauged by the way in which objects
> are represented. A primitive savage's drawing is often like a child's; the object
> engaging his attention is placed in the foreground, large and unconnected to other
> objects around it. Neither child nor savage immediately observes perspective.
> There is no uniform method of representing objects; some are in plan, some in
> elevation." (p. 25)

Yet, the Western origins and conventions of the maps Bagrow and Skelton favor are as

historically situated as any other system of signification. Cartographic projection systems,

lines, and legends can be traced back to a disciple of Aristotle. A revised history of maps

alters how we view various traditions of representation and widens our understanding of

their political, technological, and epistemological implications (Black,1997; Dubow, 2000;

Harley, 2001).

Pre-modern, indigenous peoples across the world have navigated land and sea with competency and accuracy, but they have used a different variety of materials and visual idioms. Certain Western cartographers' criticisms "that these savages couldn't draw in perspective" are unfounded. The Marshall Islanders, for instance, designed intricate patterns from palm fiber and shells to represent wave-crests, navigation sites, and mariner's direction. These accurate and useful maps provided alternate visual metaphors for navigating land and water (Akerman, 2007, pp. 57-58). Likewise, Aztec and Mayan maps were accurate, although they employed different projections and icons than European maps. Cortez conquered the Aztec civilization using their indigenous maps painted on cloth. Afterwards, invaders systematically destroyed these early Meso-American maps, replacing them with Spanish ones. We can locate a variety of visual methods that enabled different groups of people to navigate their terrain, find locations in the land they explored, and mark their territories with alternative measuring devices. Navigating the highways of life would involve very different visual icons, projections, and embodied experiences if Aboriginal culture had colonized the world instead of European (Said ,1985, 1998; Diamond, 1999). Astronomical maps are some of the oldest in civilization. The first star maps were painted on prehistoric cave walls (Lewin, 1993). Many indigenous peoples mapped the night sky. For example, Aboriginal bark paintings depicted as fishermen the familiar stars we take to be Orion's Belt (Morphy, 2001). Likewise, the Mayans mapped stars, symbolizing the Milky Way as a cosmic monster (Freidel, Schele, and Parker, 1993). These instances show how astronomical maps characterize the mythic imaginary of the dominant power that produces them.

Contemporary astronomy and its astrophysical maps of the universe also reflect the conventions from which they have evolved, even if they have become transparent to us. We draw upon the astronomical mapping conventions that were developed at the dawn of

telescopic star catalogues (Ferris, 1982; Geller and Huchra, 1989; Jaki, 1990; Kaufmann,

1991). With our twenty-first century scientific visualization techniques, we integrate

digitally-mediated star catalogue data and the spatial relationships it expresses with a

standard CGI Renaissance-perspective projection to build a 3D, virtual Milky Way (Figure

23 and Figure 24). The flights we choreograph through our virtual galaxy are exemplified
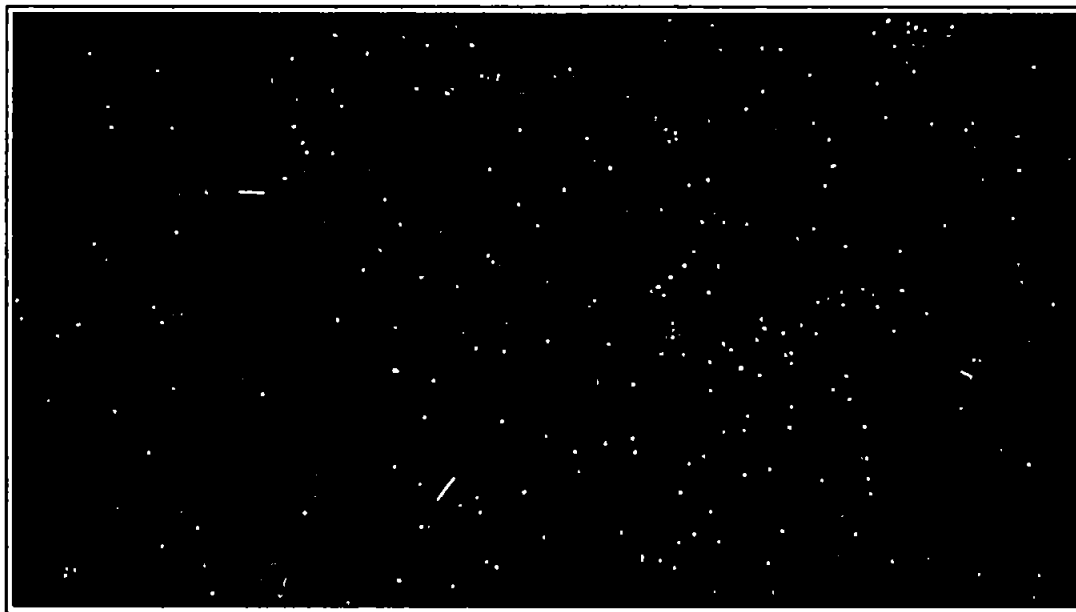
Figure 23. Virtual Flight from Milky Way to Virgo Cluster, *Runaway Universe* version, first frame. From the earth-centric view, we see the three-star belt of the Orion constellation. We "lift" off through the galaxy and visit nebulae and other points of interest on our way out of galaxy to Virgo.

in the Practicum Compilation DVD (see 1.5 Milky Way Virtual Flights, 4: *Black Holes:*

The Other Side of Infinity digital-dome excerpts, and 5: *Monster of the Milky Way* PBS

show excerpts). Like the historical maps used for colonizing the world, our modern

astrophysical maps inspire and motivate our audiences to further explore and occupy

unfamiliar territories (Haynes, 1997). Through such modern, virtually experienced, digi-

epistemological mappings, we may reinforce a dominant worldview of technology-

informed scientific fact, when in truth science is in a continual process of modifying and

interpreting results.

Figure24. Flight to the Milky Way galactic center from underneath the galaxy into the bright bulge.

In *Guns, Germs, and Steel: The Fates of Human Societies*, Jared Diamond (1999) emphasizes maps as an invention, analogous to writing. Their form, content, reproduction, distribution, and use depend on the technologies available in the societies of their making. Diamond argues that inventions originate in societies that are ready to make use of them, in terms of both their resources and ambitions. Diamond argues, for example, that writing flourished where agriculture succeeded on a mass scale, requiring elaborate systems of accounting. The agricultural success in these societies was typified by the domestication of animals, which allowed for increased food production that supported areas with high population densities. Such areas placed more people in closer proximity, which meant that ideas were transmitted more rapidly. Similarly, Diamond argues that maps proliferated in certain cultures because of their cognitively and economically fertile environments.

Also important for the development of new communications technologies such as visaphor is a sense of experimentation, of play. Diamond argues, that "technology develops cumulatively, rather than in isolated heroic acts [...] it finds most of its uses after

167

it has been invented, rather than being a foreseen need" (1999, pp. 245-246). We might

expect, then, that post-industrial societies such as our own--with abundant resources and a

significant number of professional and serious hobbyist technophiles who range across

communications media in production and consumption--would provide a perfect site for

the invention and continuing evolution of visaphor.

As is the case in Margulis and Sagan's evolutionary theory, Diamond considers

technology to be an evolution from nature, an expression and extension of the natural,

which is itself a mapping from one domain to another, a metaphor. From a biological

point of view, the mechanism for the cellular, or microbial, transmission of genetic code is

similar to writing, maps, and visaphor. They are reproductive technologies that facilitate

the spread of concepts. Visaphors may, in particular, be viewed as evolving through an

autopoetic, symbiotic process that Diamond understands as characteristic of human

societies: the "amalgamation" of smaller societies into larger, complex ones. For human

beings, amalgamation is similar to the biological principle of symbiosis, in that it describes

diverse components unifying in such a way that the unit preserves complexity and diversity

within its midst. However, Diamond holds a more negative view of cooperation than

Margulis, viewing it as a means of minimizing external threat: "amalgamation occurs [...]

in either of two ways: by a merger under the threat of the external force, or by conquest"

(1999, p. 289). He uses as an example the Cherokee Indian confederation of the eighteenth

century that was organized to resist European territorial incursions. These different senses

of cooperative motivation are not mutually exclusive; they may be determined in response

to environmental factors. Applying this reasoning to our own era, we can see how the

growing ubiquity and globalization of telecommunications is leading to the development of

new media, which are now more than ever before supported in their invention (e.g., the

open source software movement) and dissemination (e.g., social networking and sharing).

168

The visaphor arts in particular--as time-based, data-based, experiential maps--have

depended for their evolution and transmission on the digital geography and ecology of the

Internet, which has provided an especially fertile environment (Smith and Kollock, 1999),

one that has grown out of creative synergy as well as commercial competition.

When we view data-driven scientific visualizations as a modern evolution of

cartographic invention, we gain the ability to see how visaphors draw upon the visual

language of map making, employing the conventions of visual geography. Not only have

cartographic conventions influenced how visaphors depict information and arrange their

audiences' sensory experiences, but they also influence how audiences cognitively process

and perceptually experience visaphors. In the modern era, the mechanical reproduction of

maps has spread their visual language far beyond cartographers. Contemporary

communications technologies, from television to the Internet to cinematic environments,

have only further assured that today's audiences are more and more capable of reading

such visual signs.

Viseotelecommuning

Visaphors may be thought of as abstract, multilayered cultural artifacts that

incorporate color, spatial motion, and numerical symbolism to communicate a wealth of

knowledge and scientific observation. They transmit cultural matter with greater vitality

and dimensionality than that "old saw" of a Grecian urn. The embodied audiences who

interact with visaphors serve as individual carriers who recycle this visaphoric experience

back to culture. Visaphors have permeated our culture as icons, much like the NSF Net

(Figure 10) visualization study of the Internet, which is still being repurposed and recycled

through our visual, cultural library (Dodge and Kitchin, 2001). Especially in our age of

mechanical reproduction and telecommunications, visual metaphors take on viral qualities as they travel from one host to another, rescripting their visual DNA. Visaphors draw from scientific-numerical metaphors, storytelling, artistic rendering, and cultural context to provide feedback into our collective, cultural agency. This intense, digital telecommunicative interaction that I call "viseotelecommuning" is a vast, symbiotic operation.

Viseotelecommuning is similar to Norbert Wiener's understanding of the cybernetic: a social-communication feedback process (Packer and Jordan, 2001). Such a cybernetic process plays a role in what George Dyson has analyzed as the evolution of a global intelligence (Dyson, 1997). Technology is not only an extension of human beings, but is also an integral part of our evolutionary process. Complexity Theory has looked at how technology and economics evolve as evolutionary co-processes. I believe that, similarly, in contemporary society the combination of telecommunications and computers is symbiotic with human evolution. The creation and consumption of visaphors is a woven, golden thread that can be traced through the fabric of our modern, cyberspace environment. It is also a thread that can be traced as a viseotelecommuning mechanism that has shaped the creation and consumption of visual artifacts since humans began to make tools. In particular, this cybernetic process—a nexus that converges man and machine, technology and biology--involves the incorporation of scientific simulation and its accompanying symbolic-numerical math (math metaphors), use of supercomputers and digital technology, power of high-speed networks, and human agency (embodied minds that metaphorize and visaphorize).

As part of this cybernetic process, audiences do not passively consume visaphors. Collectively an audience and the individuals within it interact with the digital reality painted on the techno-digital environment. The color of a supernova or colliding galaxies

170

does not exist in alienation on the computer screen. These images catalyze physical and cognitive capacities in the embodied audience. As the displays provide transmitted light from radiating red, green, blue projector guns, the experience of the individuals is both subjective and objective. The audience brings to the table both individual and collective agencies. Agency is a crucial, emergent property of this collective, aesthetic experience.

The audience's viseotelecommunion is not about sensation alone, disengaged from context. While attending a digital dome show, the audience experiences a scientific narrative; visaphors are placed in a defined and storied context. As a result, the audience's visceral interaction with visaphoric art is related to previously experienced cultural patterns and patterns observed in nature. Thus, the visual has the potential to enable audience agency, allowing individuals to dislocate and relocate during a scripted experience. For example, the natural pattern of the *splash* will be recognized, felt, by audiences regardless of context--even, say, when mapped onto a cosmic one. We recognize a splash from our embodied experience with water. However, we also recognize the numerical digital and pixilated *splash* of a supernova or big bang. Our species-level, embodied experiences provide visceral references as we negotiate these metaphorical maps. Similarly, colors provide a point of reference for us as we make the leap from our instrumental, postmodern reality to a technoetic one--the technoetic being the juncture between art, technology, and the mind as theorized by Roy Ascott (2006). Our technoetic reality is one we digitally construct, acquiesce to, participate in, and confound. Like natural patterns such as splash and color, visaphors play a role in helping us to negotiate cybernetic spaces. They do not passively represent reality; they interactively support us by weaving golden threads of embodied understanding, of digi-epistemology, from the individual to the cultural, from our personal, sensorimotor cellular structures to our shared, grand accumulation of

171

knowledge about the universe. In this sense, visaphoric mapping is a mystical transformation, a visual alchemy.

Yet, this visaphoric alchemy helps to demystify science for the general public within the context of the shows' scientific narrative. It is the visaphoric relationship to the story that exposes the scientific processes. For example, in the *Hunt for Supertwister* PBS show, *Monster of the Milky Way* PBS show, and *Black Holes: The Other Side of Infinity* digital-dome show, the visaphors are set within stories about the social process of people "doing" science: hunting for supertwisters or discovering black holes. The narrative features visaphors as part of the discovery adventure. Visaphors not only provide a virtually embodied experience, they also act as windows into the esoteric computational process, bringing numeric symbols alive with motion, color, and physical dynamics. The narrative context enables people to participate in scientific problem-solving and strengthens the power of the visaphor through its participation as a character within the story (Latour, 2002, p. 22).

We may conceive of visaphors as "immutable mobiles" in Bruno Latour's sense of the term (1979). We can present, read, or combine them within other contexts (Figure 19). In contrast to the background of a scientific story, visaphors can play an important role within interactive contexts such as a museum kiosks or interactive websites. For example, my AVL team and I are re-investing the tornado visaphor we used for *Hunt for Supertwister* in a new "Science Storms" interactive kiosk at the Chicago Museum of Science and Industry (which is set to go live in Spring 2010). Such interactive applications of visaphoric art are beneficial to teaching the public about the computational scientific visualization process; it complements our work in public shows (Gordin and Pea, 1995). Such interactive learning contexts are important and deserve an in-depth treatment, which is beyond the scope of this thesis.

Signifying Embodiment

For the remainder of this chapter, I will discuss some of the most important systems of embodied signification visaphors employ, with a special emphasis on color. I emphasize color because it tends to be a ubiquitous but often overlooked aspect of signification in scientific illustration, and most especially in data-driven visaphors, in which most lay audiences and some specialists viewing outside their domain are unaware of the choice ranges available to data-viz artists, such as when satellite images are recomposed and colored, seeming to display unaltered photographic data. I also emphasize color because it has special meaning for me. Color has dominated my work from painting through photography to digital imaging. I began my artistic career as a colorist and have long considered the impact color has on viewers, its sense of extra-linguistic immediacy; ability to convey emotion and energy; and potential for plasticity, especially when manipulated with shape and motion over time. In my early work I explored color as a function of scale by creating computer-generated images of a finite size that scale up to wall-size collages that I call "compulages." I have since expanded upon this idea of color filling the visual field and exploited this phenomenon on large-scale and immersive environments such as IMAX screens, high-resolution digital domes (Cox 2003a) and 4K stereo theaters.

In my later work, I have become especially interested in color as a great case study in the boundaries of "reality" and collective and personal experience. Color negates neither a physical reality nor subjective experience. By pointing up the "fuzzy" boundaries between them, it provides us with a better understanding of how sensory perception functions. Color perception straddles a philosophical edge that crosses many soft and hard

173

sciences, yet it is not a well understood phenomenon after all our psychological and scientific research. Color begs the question of "reality" and whether we construct or discover it.

Color as a Case Study in Perception and Mapping:

Along with data modeling, color provides one of the two basic elements that make up more complex metaphors. When applied through visualization, color may be understood as a basic visaphor. Color functions as an essential dimension of visual mapping, as numbers are scaled from a computational model to some model on the screen. Put another way, cyberinfrastructure (CI) is the technological fabric that enables a new art of scientific visualization. The CI environment is a cybernetic workbench, and supercomputer data is the raw material used to construct things upon it. Simulations and visualizations sometimes take days or weeks to solidify there. As I work, the computer enables me to orchestrate millions of colors and to compress space-time from billions to millions of light years. The hours pass quickly during the virtual experience of testing and cooking color combinations within a million pixels, while I intermittently check the trays in the oven.

Up through the present, studies in scientific visualization have tended to emphasize perceptual color response. However, visaphors involve two types of color response: perceptual and conceptual; immersive and cyberspace environments evoke both, between their pixel radiation and numerical symbology. Studies in color perception have established that both physical and mental properties consign color in humans. The sensation occurs as an internal, physical, and perceptual process within the human visual and mental system. It is a perplexing phenomenon. Things in the universe do not possess

174

color as they appear; rather humans create color within their individual psychological experiences from a variety of external stimuli. Color sensation can create its own perceptual structure, or it can help delineate pre-existing morphology. Color perception is a selective faculty; that is, not everyone can experience it in the same way. A significant portion of the human population, for example, eight percent, is color-blind (Bucke, 1961; Birren, 1978).

The colors we generate from digital technologies recapitulate the colors that we can behold. The experience of colors with which we are already familiar provides an iterative dimension of the metaphor, although their application may be novel, even surprising, given a particular animation event or context. As a data-viz artist, I am constantly reminded that color is inherently illustory. In computer graphics, I wield a multi-million color palette. My artistic / design / scientific intent determines how scientific data, as raw material, will host this color. As I make these choices, I am also aware of how color is one of the most used and stimulating devices in art practice. From Kandinsky to Monet to Albers, color is the artistic tool within which both clarity and illusion emerge (Albers, 1963; Itten and Birren, 1970). In conventional scientific visualization terms, color can confuse as well as reveal data; in my view, however, color plays an even more significant role.

Within the arts, we accept that color serves as a symbolic medium for emotional expression, which has been a long-standing convention across world cultures, and one theorized and employed through modernity by expressive artists (Arnheim, 1974; Kandinsky, 1977). Color and its perception have especially informed my image-making research and practice. For me, color design is an area of study that combines art and science, technique and technology. Johann Wolfgang Goethe, an artist, and Michel Eugene Chevreul, a scientist, discovered simultaneous color contrast because they were enamored with color (Chevreul, 1839; Goethe, 1840). Although an appealing artistic

175

device, it can be an obstacle to scientific visualization. As an artist working in traditional media, I have exploited simultaneous contrast in acrylic paint and photography. With care, I have explored and incorporated simultaneous color contrast as an effect in my scientific/artistic visualizations through digital pseudo-color.

Pseudo-color is a term that describes a process that is often used in the making of scientific images. Pseudo-color is a digital or telescopic filtering method for delineating the range of density values and thus morphology in an image.[4] Psuedo-color is in many ways a mis-metaphor because, in a perceptual sense, all phenomena are falsely colored through the discrete perceptual system. Color is an outcome of our relative experience rather than an inherent property of the object and its surroundings. Our shared subjectivity yields the illusion of objectivity; and this shared subjectivity renders the world into very luscious and useful visual stuff. Yet, this illusion of objectivity is always already a social construct. In *The Need of Perception for the Perception of Needs,* Heinz Von Foerster (1989) dispenses with the sacred notion of human observational objectivity in arguing that the biological basis of color and other sensations is created mentally by operations in the nervous system: "It is here that the quantities of sensation are transformed into the qualities of perception, where each of us creates the world as he or she perceives it" (p. 225). In a perceptual sense, color is a metaphor. We perceive one thing in terms of another. We internally map color within our visual system. Our everyday personal "experience" of color is mediated by fashion, habit, history, health, and situated awareness. Color may be illusory, but for most people it is an essential characteristic of being human and necessary for negotiating the world. The study and control of color continually reminds me of the evolution of consciousness and the illusory nature of the universe.

---

[4] Telescopic data receives color through a selective filtering process. In digital computer graphics, pixel look-up tables of red, green, and blue combinations provide color within the scientific data.

The cognitive and psychological study of color demonstrates important interplay between subjectivity and objectivity, pointing to the relativity of our conceived experience of external reality (Berlin and Kay, 1969). The study of color from various disciplines accentuates and confirms the relativity of our perceived reality. Some psychologists suggest that color response is an evolving universal faculty within culture and consciousness (Albers, 1963; Bucke, 1963; Berlin and Kay, 1969). Others theorize that color demonstrates powerful psychological, biological, and emotional effects through its historical emphasis across cultures (Itten and Birren, 1970; Birren, 1978; Ware, 1988; Healey, 1996; Rogowitz, 2001). Modern medical and consciousness studies continue to suggest the experience of color is relative (Carruthers, 2007). Color is one of the most studied yet fugitive of perceptual phenomenon.

From the perspective of some cognitive approaches, consciousness is much more than our perception of the qualitative senses. We are reminded of Black's interactive theory of metaphor as Lakoff and Johnson describe the interactive, and so inherently metaphorical, nature of color. They emphasize how color does not exist in the world externally, despite our perceived experience of it as something we find outside of ourselves:

> "Color concepts are 'interactional' concepts; they arise from the interactions of our bodies, our brains, the reflective properties of objects, and electromagnetic radiation. Colors are not objective; there is in the grass or the sky no greenness or blueness independent of retinas, color cones, neural circuitry, and brains. Nor are colors purely subjective; they are neither a figment of our imaginations nor spontaneous creations of our brains." (Lakoff and Johnson, 1999, pp. 24-25)

Varela, Thompson, and Rosch take a similar approach in *The Embodied Mind* (1991), describing color perception as a structural coupling between the body and the environment. They use color to show how perception forms a mysterious interface between an autopoetic unit embedded within an environment (which can also be another autopoetic

177

system). The perception of color, they argue, has evolved and adapted as part of the physiology of the brain, the mind, and its interaction through sensorimotor processes within the environment. Humans have evolved a trichromatic neural color capacity that is particular to primates. Because our structural coupling between our neural-visual system and the environmental is very different from other species, we inhabit a different type of embodied reality, but our color reality is no more valid or "real" (pp. 181-184).

The fact that color does not exist apart from us, "out there," sends a powerful signal of our postmodern existence, one complemented by the Heideggerian-based, phenomenological thought of Maurice Merleau-Ponty (what he called "being-in-the-world") and grounded in the contemporary scientific and cultural studies that followed after (Merleau-Ponty, 1962). The act of coloring scientific visualizations as we render them is, then, not so much a process of re-discovering or revealing an existing, concrete, material reality as it is a process of constructing that reality.

For example, in Practicum Compilation DVD 3: *Hunt for Supertwister* PBS show excerpts, Scene 5, Sequences 1-4 we use dramatic color differences to structure the visaphors. In Scene 5, Sequence 1: Volume-Rendered Tornado visaphor (Practicum Compilation DVD 3:5.1), we employ voluminous, dark-charcoal grays, reminiscent of on-coming storms. In Scene 5, Sequence 2: Glyph Tornado visaphor, color brilliantly defines the arterial, inner mechanisms of the tornado. On the other hand, Scene 5, Sequence 3: Alternate Doppler Radar-Rendered visaphor references two-dimensional Doppler views of the same data-driven storm, visually attaching the audience to familiar weather patterns. Yet, Scene 5, Sequence 4: Spotlight Vortex-Rendered visaphor focuses a bluish searchlight on the ethereal vortex that shapes a ghostly tornado, providing an alternate data-driven construction. Color psychologically and perceptually informs these diverse visaphoric models of the same simulation data.

178

Colors are sometime altered when a visaphor's viewing context is changed. I had,

for instance, originally approved colors scenes for *The Black Holes Project* to match

telescopic images, in order to enhance the connection between the reality of scientific

instruments and the digital reality on the screen (Figure 25, right side). For the Leonardo

DaVinci Exhibit at the Chicago's Museum of Science and Industry (MSI) in 2006, I

repurposed the colliding galaxies visaphor (Figure 25, left side). Because I was present as

an invited artist, which gave me a great range of aesthetic freedom, I chose a vibrant color

harmony that appeals to my personal sensibility (See Practicum Compilation DVD,

General Visaphor Sequences, Colliding Galaxies 1:4.1).

I compare this coloration to *The Black Holes Project* version on the right (See

Practicum Compilation DVD, General Visaphor Sequences, Colliding Galaxies 1:4.2), in

which I approved muted colors similar to telescopic optical imagery. The MSI version on

the left intensifies the plastic nature of the interpenetration, like paint mixing, creating an
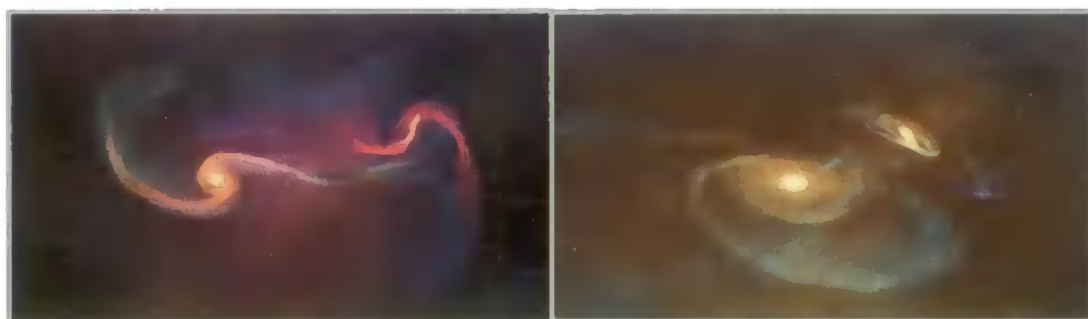
Figure 25. Colliding galaxies color comparison: left image from Leonardo da Vinci exhibit in
Chicago's Museum of Science and Industry (MSI) and the right image from the *Black Holes* dome
show. On left, the MSI version has vibrant color harmony; on the right, colors designed to simulate
Hubble-like telescope filters.

extra color dimension in taffy-like silk. Both visaphors statisfy the goal of showing the

galaxy merger. Yet the MSI rendition celebrates its inherently digital nature, with no

pretense to reinforce expectations of the oxymoronic "realistic" pseudo-colors from the

Hubble telescope (Figure 25, right side). In this case, I felt free to apply a broader range of

colors, drawing from the full spectrum of what humans can perceive rather than those color

segments used conventionally in coloring images derived from instruments. Typically, science educators tend toward conservative color palettes, based on a history of muted, supposedly realistic hues in science illustration (despite the fact that, for example, actual internal human anatomy fails to register for most viewers in pastels). When given license, I prefer more striking, vivid color ranges: jewel tones and complementary contrasts.

Creating visaphors, including coloring them, is a metaphorical act of becoming, groping as directed chance, using our tools and current, collective knowledge for sense-making and discovery. We are participating in collaborative processes that emerge from artistic, scientific, and technological discourses and practices. Color enables visaphors to cross between these domains to delineate shape, deploy numerical values, differentiate forms, and further reinforce other visual metaphors. Color not only maps numerical symbols into pixel values, but it is also maps scientific models to their cultural contexts and expectations.

Visaphors circulate within their own color reality, one that is relative to their consuming audiences as well as to their creators. An audience does not passively consume them. When an audience sits in a digital dome and experiences a visaphor, its members' bodies interact with the digital reality painted across the immerse environment. The visaphor engages viewers in a multi-sensory experience, one that individuals perceive and conceive in their own ways through filters of personal embodiment and psychology, as well as any cultural filters they may have internalized over time. The experience creates a feedback effect between the audience and the visaphor: the color of the supernova does not exist in alienation from them on the computer screen. Colors are realized through interactions between the physical and cognitive capacities in the embodied audience. While the displays provide transmitted light from radiating red, green, and blue projector guns, the experience of individual viewers is both subjective and objective.

180

Color design is essential to our practice. My team and I created, for example, a powerfully colored, animated sequence of the first star going supernova (Figure 20) for *The Black Holes Project* (see Practicum Compilation DVD General Visaphor Sequences, Star-Galaxy Formation, 1.3.1). I colored the visaphor to suggest a fetal star germinating within a seething red-orange nursery of hot gas, contrasted against the bubbling, distant background of the immersive, hemispherical, digital screen. After the star bursts forth, its short life ends in a pinwheel of complementary red and gold blowing debris and dust particulates to the periphery of our visual field and beyond. Because what the audience sees relates to their sensorimotor experiences of other things, they experience the images viscerally--despite the fact that we are viewing a data-driven sequence that shows the dynamics of stars and gas mixing over a span of millions of years. Through the audience's embodied experiences, they are predisposed to relate sensually to the view of color spilling and mixing on a three dimensional surface (Figure 20). The audience groks the visaphor without having to analyze it as a multilayered outgrowth from metaphorical mappings that originate in both the art and science of scientific visualization. Given that the visaphor's viewing context is an educational, scientific narrative in a museum, the audience might have received a lesson in cosmic evolution that is mainly cerebral, informative, spare. Yet, I deliberately mix the colors on the screen to provide them with an enveloping, sensual experience. Even the motion of the camera, as it smoothly penetrates this act of becoming, is intended to augment the audience's sense of their flowing radiantly together. This sensual flow is experiential, subverting formal and didactic expectations.

Space and Time:

The symbolic systems we use to express scientific concepts may not be immediately comprehensible to popular audiences; they often require training to understand fully. However, popular audiences in first-world societies already view scientific visualizations within documentary settings with a trained eye. When viewers watch the *Black Holes* digital-dome show, for example, they view galaxies and stars that are projected into a 3D, Cartesian coordinate space, one made familiar through our Western "languages" of maps and computer graphics. The camera's smooth and majestic flight through intergalactic space, faster than the speed of light, is made sense of to audiences through concepts of constructed and mediated point of view that our techno-science culture has transmitted to us. Viewers do not imagine they are journeying through the void itself, or even necessarily that the camera has done so. Some specialized forms of scientific visualization are rendered comprehensible to the public through their association with now popular forms (that may once have been marked as specialized) and repetition. Glyphs within scientific visualizations (such as the cones we used to represent ground
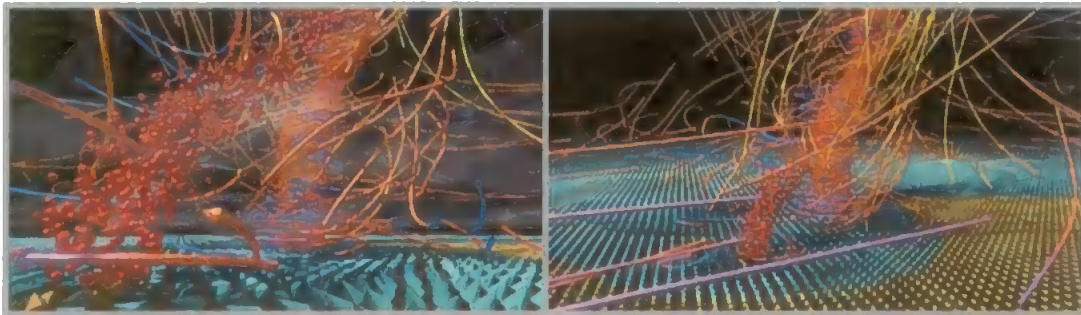
Figure 26. Cinematic scientific visualization: <u>Above left frame</u> is a storm chaser view, low to the ground with a "close-up" of both tornadoes. <u>On the right</u> is an aerial view of the same time-frame in the tornado movie sequence. This aerial voyeur's view removes the tornadoes to a "safe" distance.

wind direction in 3D tornado visualization), for example, are relatively novel within the scale of technological innovation, yet they are understood by audiences because of their

182

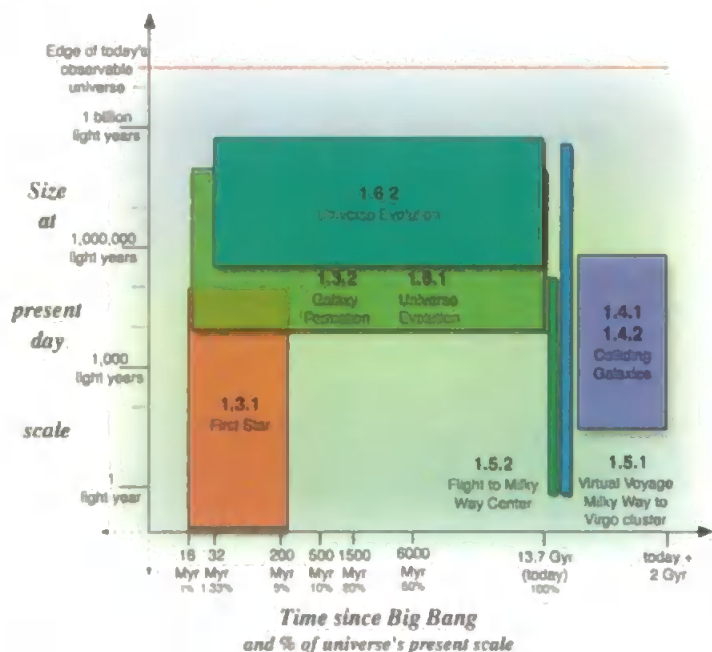similarity to the sign language of maps and their frequency in representing science stories. Visualization artists can enhance the immediacy and comprehensibility of their work through emphasizing the conventional and associating novel elements with the familiar. We may, for example, adopt techniques from popular cinema in order to render science stories more clearly and vividly, such as focusing on the most significant aspect of a phenomenon with a camera "close up." For example, Figure 26 demonstrates this cinematic language when viewing the two tornadoes: one view is a "close-up" and the other is at a voyeur's distance. The impact is greater during the immersive dome experience (compare Practicum Compilation DVD, 1: General Visaphor Sequences, 1.2.1 and 1.2.2). Audiences understand popular media methods for relating and dramatizing narrative; they readily interpret projected perspectives and fictionalized scenarios--the hypothetical extensions of embodied experience.

In addition to drawing upon familiar cultural mediations of experience, visaphors created for popular audiences may also choose to emphasize actual, embodied experiences that are accessible to all, and use those experiences to evoke sensation and emotion that may express or reinforce ideas. As in the case of color, our relationships to space and time are mediated by our sensorimotor faculties within the environment. The interaction of the two shapes our perception, and in return our perception shapes how we conceive of our environment. "Every living being categorizes." Lakoff and Johnson write, "Categorization is therefore a consequence of how we are embodied" (1999, pp. 17-18). In other words, our sensorimotor-neural structure and conceptual structure share integrated processes. A human being perceives, organizes, stores, and recognizes basic categories as single mental images that they can sort into further mental classifications. We classify what we perceive into mental constructs so that raw sensual "input" does not overwhelm our cognitive system. We simplify these categories into conceptual and verbal container abstractions, or

183

constructs. Characteristics like shape, color, and motion all feed into this gestalt

perception. Concepts of time and space, according to Lakoff and Johnson, are essential to

the development of language, and, so, by extension, to symbolic systems for describing,

interpreting, and encoding the world, including visual ones. We build our abstract

concepts from our earliest explorations of the world, coupling our bodily sensorimotor

experience with symbols that name and story them (1999).

Within scientific visualization, the science stories we tell visually are significantly

defined by how we sequence them, the speed with which we render sequences, and how

we position them and the angle by which they are viewed within space. The temporal and

spatial dimensions of rendering are not incidental, but fundamental, to how audiences interact with visaphors. In the visaphors I directed as part of *The Black Holes Project*, for example, representations of time and space are significantly mediated.

Figure 27. Space and time location ranges of General Visaphor Sequences from astrophysics computations. On the vertical axis, scale is measured in light years; the horizontal axis shows time measured in millions of years.

Billions of years are compressed into a few minutes as astrophysical objects evolve:

galaxies collide, the universe ages. The actual space of millions of light years is

compressed into a virtual space that is 4000-pixels wide. In cinematic visaphor sequences

such as those we used for *Runaway Universe*, visaphors enable viewers to travel faster than

184

the speed of light so that they can make a virtual tour from our Sun to reaches of space, clusters of galaxies, beyond the Milky Way. Space and time are distorted artfully: metaphorically remapped to an embodiment on a human scale (Figure 27). We do not necessarily use the same scale of time, however, for all visaphors, not even cosmic ones. The time scale we used for our visaphor of the universe's evolution is very different. For example, Figure 27 shows the relative space-time of various visaphor sequences. Compare the visual experience of the Evolution of the Universe, *Runaway Universe* (Practicum Compilation DVD, 1.6.1) with the Evolution of the Universe, *Black Holes Project* (Practicum Compilation DVD, 1.6.2). The underlying simulations are similar in time and scale; however, we provide a distinct experience through complementary color and cinematic treatment.

Yet, the resizing of phenomena to a human scale does not tell the whole story of how and why a scientific visualization artist chooses to manipulate cinematically the plastic media of space and time. As I have claimed above, the ways in which we represent space, time, and their continuum also serve to define the science story that a visualization tells. In *The Black Holes Project*, we consciously developed visual metaphors to convey Einstein's understanding of space-time, especially how it is warped by the incredibly dense presence of black holes. In *Runaway Universe*, we visually metaphorize the unexpected speeding up and continued dispersal of galaxies following the Big Bang (a scientific discovery that runs counter to our common sense view of the tapering of energy and its effects on matter following an explosion).

Scale / Projection:

In scientific visualizations, the range of scale with respect to size can go from the microscopic to the macroscopic, whether the phenomenon being represented is the mechanism of a nanobot or the heart of a galaxy. Visualization artists are conscious of this type of scale as both an informal spatial rubric for comparing the relative size of things and as a formal technical ratio between a unit of spatial measurement that is mapped to an equivalent unit of actual size in some phenomenon. We provide a scale not merely to document the physical dimensions of phenomena, but to orient audiences, providing an aid that helps them relate a representation of the natural world to their own embodied experiences of it. Since the empirical revolution in Western mapmaking, which occurred in the seventeenth century, a record of scale has been viewed as an essential inclusion, nearly as essential as the lines of latitude and longitude that fix a place to the globe (Bagrow, 1985; Akerman and Karrow, 2007). However, the typographical reminder of scale inscribed upon a visualization—call it a map—also reminds viewers that they are viewing a construct and that they should therefore undergo the cognitive exercise of interpreting it as an abstraction at a remove from lived experience. They are made self-aware of its qualities of projection and distortion. In the visaphors I direct for immersive displays, I have made a conscious decision not to impose a reminder of scale, despite its explicitly educative value. Likewise, I omit color scale or other diagrammatic elements associated with particular conditions, despite their usefulness in orienting general audiences. Even when incorporating a grid plane, the intent is suggestive rather than denotative (see Practicum Compilation DVD 3: *Hunt for Supertwister* PBS show excerpts, Scene 3, Sequence 1 Volume-Rendered Tornado visaphor only).

186

Visaphors designed to be experienced, to have wide appeal and visceral impact, suffer from cumbersome and didactic numerical scales. What we lose in the precision that interests experts, we may gain in the intuitive understanding of popular audiences. I have arrived at this practice through experience. When we collaborated on our first space show with the Hayden Planetarium in New York City, the educational committee encouraged the inclusion of scale markers. They used diagrammatic idioms to flip through numbers to impress upon the audience the jump in scale and the evolution of time as the camera moved viewers through a tour of the universe. However, in *The Black Holes Project*, my AVL group and I avoided scales and diagrammatic elements. My artistic intent was to provide an immersive experience for all of our visaphor segments. We were conscious that some key elements of scaling remained invisible to the audience. In fact, in observed telescope reality and scientific calculations, galaxies are very, very far away from each other in astronomical proportions. In order to give viewers a visually stimulating encounter and a coherent sense of flight, we needed to shrink the distance we showed between galaxies, although we did so to scale so that the relative distances are preserved. In practice, we chose to scale the galaxies themselves, rendering them four times larger than actual in order to shrink the vacuous space between them (see background galaxies in Figures 23 and 24). In the Practicum Compilation DVD's General Visaphor Sequences, Milky Way Virtual Flights, *Virtual Voyage from Milky Way to Virgo Cluster, Runaway Universe* (1:5.1), scale has been manipulated to give the audience a smooth, integrated experience of movement from our central point in the Milky Way, out of our galaxy in, and into thousands of galaxies beyond on the virtual voyage to the Virgo Cluster of galaxies. I grant that in doing so, we lose an opportunity to convey some information and may have exaggerated other information. This may be of particular concern to those who view scientific visualization as a rare opportunity to educate the public about scientific

187

fact. However, we must ask ourselves what the goal of such large-scale scientific outreach is--a qualitative experience of the universe or a numerical/quantitative one? Given the data-driven nature of computational scientific visualizations, we could say the numbers are already mapped into a visualization's motion dynamics.

Yet, I believe the key justification for such data transformations is that when visualizations provide more immediately embodied experiences, they are more readily understood and more deeply felt by audiences than they would be in symbolic form. We can give audiences a very effective sense of the power of an F3 tornado's extreme wind sheer without displaying its kilometers per hour. What is more, sometimes the cultural images we choose to associate aesthetically with certain scientific ones can deepen audience impact, even when they are not strictly scientific or informational. Representing the birth of a new star as a Buddhist mandala, for example, may express something of its wonder and cosmic significance that scientific simulation alone cannot. We ought to acknowledge to ourselves that although the science stories we tell matter, their numbers can be meaningless when the goal is to create an experience for viewers, one that is ultimately not about scale but flight and attraction, arrest and sensation. Much like indigenous human stories imbued rituals and maps with a sacred aura, an aesthetic power, visaphors reciprocate vast cultural power when embedded within a human scientific story and an immersive embodied experience.

Orientation / Perspective:

Determining orientation is a conscious decision in the making of visaphors, one that is informed by conventions in popular, artistic, and scientific domains upon which we draw. Most technological innovations, such as writing and map making, proliferate through copying rather than pure innovation. Even the invention of new technical forms is

188

often rooted in non-technical behaviors and habits of thought and behavior. Writing, for example, evolved from pictures and pictograms; the efficiency of writing systems goes back even further: it is tightly coupled to pre-existing patterns of speech: phonetic alphabets (Robinson, 1999). We find this copying tendency in the making of modern digital maps. As I discussed in a previous chapter, this is particularly true of the ways in which they mimic cartographic conventions.

Scientific visualizations in general usually begin by orienting audiences within the familiar. In visualizations showing a process occurring within a spatial paradigm, the audience's view is initially focused on a familiar place. In virtual cosmic voyages, audiences "take off" from earth, our solar system, or the Milky Way, which resonate with an abstracted sense of home. In the Runaway Universe, *Virtual Voyage from Milky Way to Virgo Cluster*, we begin by orienting the camera's point of view, and thus the audience's, at a familiar place, earth (see Practicum Compilation DVD General Visaphor Sequences, Milky Way Virtual Flights, *Virtual Voyage from Milky Way to Virgo Cluster* 1:5.1). From this orientation, we look abroad into space, outer space. We see the Orion constellation, a familiar demarcation in the North American night sky (Figure 23). We then "lift off" through the rich, stellar regions of our galaxy. Along the way, we visit an itinerary of familiar astrophysical objects, such as nebula, images that have been retrieved by NASA and proliferated to a greater public. We capture "points of interest" along the way as we finally pass through our galaxy and out to super clusters of galaxies in their variety— spiral, elliptical, and otherwise—exploring territory that modern scientific instruments can only partially reveal.

The implicit geocentricism such journeys reproduce may be meant to ease viewers into an educational experience, building from what is understood and accepted to what is more alien and difficult to grasp. However, as I also demonstrated in my earlier discussion

189

of Eurocentric mapping conventions, such an orientation is loaded with political significance, communicating human dominance within the vast universe.

Through such virtual, digital technologies, we provide an embodied experience of phenomena that can only be experienced through imaginative extrapolations from known data and the theories that inform them. This, too, is a kind of orientation that scientific visualizations can assume, as artists fill in the blanks of the known, erasing regions where dragons be, replacing them with conquered epistemological territories. Our speculative physical and intellectual explorations are displaced through visual narratives of scientific conquest.

In doing so, we encourage audiences to inhabit a shared metaphorical reality of modern techno-scientific culture, one that, in many ways, serves the same purpose that spiritual myths and early maps of the world once did. As with many early pre-modern maps of uncharted territories and the spiritual imaginary, we view space and time unfold from an axis of the familiar. Even as we express our powers of epistemological conquest through fabricating a complete map of the unknown, we express a contradictory anxiety: our virtual maps reproduce, in their geocentric orientation, a premodern sense of space. Of this sense, Denis Cosgrove writes, "most nonmodern world maps thus normalize the center, banishing the strange and abnormal to the edges [...] The center of the mapping is 'home,' the familiar space of everyday life, while the world's boundaries are the edges of known space; they do not encompass the globe" (Cosgrove, 2007, p. 71). The point of view we adopt in visaphors, then, may be understood as a form of self-reference; in it we mirror a universe that reflects ourselves. Such viewpoints expose the power of assumption: within visaphors perspective remains invisible to the digital eye, expressed only as gaze and a virtually embodied motion as the gaze moves and rests--a relative,

human perspective from which to launch ourselves, still safe within the cognitive framework of our own cultural constructions, into the unknown.

Networks of Relations: Conceptual Connections

If the orientation of viewers is an artistic choice that is loaded with meaning, so too are the social constructions of place viewers encounter in visualizations as well as the connections between and paths through them. Geographical maps, to which visualization's mappings are analogous, show both geographical locations and the networks between them: rivers and roads, trade routes and migratory paths. They also show networks of relations that separate them into discrete units, such as national boundaries or grids of measure (longitude and latitude). Philosophically, maps help us to define our experience of navigating a common space (Akerman and Karrow, 2007).

By their very operational form, all maps visually metaphorize the phenomena they define. The neighbor's property line that can and must be verified by common, technological instruments defines its accuracy by the quantifiable standards of land survey and civil engineering. Yet, the property line is an abstraction, and an objectification, of a division that does not occur in nature. The further removed from direct bodily experience such an abstraction happens to be, the more room it allows for proliferating metaphors, and more complex ones at that. The idea of a place such as the Rocky Mountain National Forest is delineated by a map, not a fence (Schulten, 2007, p. 178, p. 182). Maps thus provide us with a metaphor for embodied spatial coherence. Because scientific visualizations tell science stories that are already at a remove from embodied experience, they generate such complex metaphors. When we create a map of the cosmos, for example, we establish a sense of place, suggesting, at a minimum, that the vast distances of

191

space can be made sensible to us. We populate that space with material elements (planets, stars, nebulae) that, through stories about their agency and change over time, take on qualities of characters acting in a cosmic tale upon a mythic stage. What do our depictions foreshadow? How do they characterize the actions that have come before? What are the limits of our ability to reveal and predict, and why do we undertake to do so? Images communicate such concepts, which may complement or resist, encapsulate or expand upon voiced or typographical documentary narration.

According to Matthew Edney, "three issues--social needs, power relations, and cultural conventions--underpin the production and use of all maps" (2007, p. 119). When we map through scientific visualization, we therefore need to consider not only what spaces and places, routes and boundaries, connections and separations we depict, but also what social needs, power relations, and cultural conventions they metaphorically express. Through their symbolic fixing of place and property, geographical maps have supported the political and economic purposing of land (Cohen, 2002; Edney, 2007, pp. 130-139). Topographical maps, which might be taken as purely scientific, have also been drawn for and put to use for such purposes--e.g., to record natural resources for future collection and to note advantageous military routes and positions. Within the documentary setting of scientific visualizations, the phenomena, or territories, we map are most obviously claimed as the territory of science. In fixing them within an empirical epistemology, we add nuance to our shared view of reality. However, at the same time, we denaturalize and objectify natural phenomena and we seem to make a claim of static and objective truth. We provide a vehicle for political and economic uses, which may range from the benign to the exploitative. We cannot be held responsible for anticipating all such potential uses, but we do need to consider how visualizations may be dislocated from their original contexts

and recirculated within institutional discourses as well as the informal culture of our audiences.

Consider, for example, how most historical maps were concerned with charting new territory and orienting people toward it (a view from where they were to where else there was in the world). Such maps provided inspiration to explore new territory. For example, Lewis and Clark's map of the Louisiana Territory inspired people to journey to the new land (Cohen, 2002; Schulten, 2007, pp. 174-182). The map served as a promotion for colonization of the United States after the Civil War. Our visaphoric maps likewise may be thought of as seeking to inspire the public to explore new concepts about science and the cosmos. Visaphors inspire a curiosity about the unmapped territory through the wonder of simulations and God's eye views. They promote interest and study, stewardship and interrelation, but also potential conquest.

From a popular audience's perspective, geographical maps not only identify place, but also help us to find our way through it (Akerman, 2007). When we present a scientific visualization, we must also be conscious of the routes with which we provide viewers to find their way through new territory, especially epistemological territory that is expressed in visual forms. Travel maps in contemporary culture tend to show a large political region (city, county, state, country) connected by a network of routes. They provide a wide angle view so that viewers can see the entire network of relations at once. The wayfinding they encourage is active in one sense: map users may readily see routes and choose between them. The territory between routes is not fully elaborated and the routes themselves are already established; they give viewers no sense of discovery. Visually, the focus becomes the ordering of knowledge; practically, the focus is on operationalizing it. In scientific visualizations, we may make different aesthetic choices in how we enable viewers to find their way through the maps we show, and the choices we make position viewers differently

193

toward the map and potentially the phenomena the map represents. In the *Black Holes* digital-dome show, for example, we deliberately chose not to develop a visaphor that revealed a complete network of the territory we would enable viewers to virtually navigate. We sought to give viewers an embodied experience of flying through space in a shuttle with invisible walls, propelled forward by their visit to points of interest along the way. In doing so viewers became cosmic travelers participating in a guided tour of a virtual universe. They are not in the driver's seat, but they are given a more active sense of exploration, of encountering much more directly virtual phenomena and the scientific knowledge they embody. These cosmic voyagers participate in the cultivation of the cultural imaginary and perhaps enhance visual faculties as well. In *Mental Imagery Cultivation as a Cultural Phenomenon: The Role of Visions in Shamanism,* clinical psychologist Richard Noll reviews the cultivation and potential adaptations of mental imagery across cultures from Buddhist visualizations to Renaissance European alchemy (1985). Perhaps visaphors will cultivate visual and mental capacities beyond standard learning expectations and heighten our "immersive intelligence" (Nechvatal, 2001).

Myths and Informing Narratives: Mapping Worldviews

The digital revolution and its near ubiquitous presence in mass media have brought together an even greater correspondence between science, technology, the visual arts, and popular culture than existed historically. Science is more visual than ever due to new enabling technologies and instruments, and the popularity of science—especially as an account that establishes and authorizes what is valued and real--has increased dramatically in the twentieth century, and continues into our own. Concurrently, popular culture has become increasingly visual, reflecting the increasingly visual capabilities of mass media and social networking technologies. It, too, has become a venue for establishing value and even what is real, at least in terms of urban legends and contemporary, alternative beliefs that, although not scientifically documented, are sometimes accepted as fact.

Modern educational theorists have sought to join the two together through the concepts of informal education that takes place outside of the classroom and ubiquitous learning that employs distributed technology for engagement. Yet, scientific and popular cultures are already in communion with one another through the circulation of myth and the images that help us to populate, elaborate, and make sense of experience. The very culture-stories we tell about the nature of ourselves and our existence permeate the discursive boundaries between the two, despite differences in authority and epistemology. Although popular audiences may not understand in detail or even the fundamentals of the scientific content of a visaphor, they readily understand its use of conventions borrowed from cultural forms with which they are familiar, stories and images they recognize.

Cinematic visaphors, for example, often tell a story of birth and death, of creation and dissolution, since they typically show a phenomenon in all its complexity forming,

195

existing, and returning to a previous point of disintegration, in which contributing systems

to the phenomenon as complex system cease to interact in a higher-order, generative way.

This formal tendency implicitly associates visaphors with myths of existential beginnings

and endings, etymology and eschatology. The science stories visaphors tell make literal

sense of the cyclical nature of phenomena, from the birth of stars to their explosions or

implosions, from the formation of supercell storms to the diminution and cessation of

twisters. Yet, the story is given emotional and cultural associations through how it is

depicted visaphorically. A twister's formation may be shown as a violent clash of

disparate environmental forces or as the harmonious attraction and interaction of natural

elements. It may be made to appear monstrous, imbued with a terrible intelligence, or

naturalized as an instance of elemental chance, a terrible accident associated tacitly with so

many others of different kinds. It may be shown as a formally realistic natural

phenomenon or anatomized fantastically with glyphs so that it seems no more dangerous

than the diagram of a machine gun at rest.

We may be inclined to view science and myth as separate from one another as

modern and ancient societies are by time. However, in *The Myth of the Eternal* return,

Mircea Eliade makes a compelling case for acknowledging some continuity in how we

story the existential (1971): such narratives answer compelling emotional needs that, in

remaining relatively constant over time, return us to similar bases for consolation. In a

well-known illustration of mythic return, Eliade associates Einstein's theory of relativity

with archaic rituals of regeneration: enacting symbolic events that embody the cyclical

nature of time and the cosmos, and thus signifying their determination of human existence

and experience. Einstein's theory of relativity recapitulates such a view by expressing how

our environment and our relationship to it are mediated directly by space-time.

Thus, although visaphors and their informing systems of data and mathematics are created explicitly to communicate scientific knowledge, we may expect to find that the creative imaginary they employ calls upon a catalogue or library of visual forms that are culturally-dependent in meaning, arising again and again in our visual history. Like other visual art forms, visaphors participate in recirculating archetypal images that are rooted in myth. The sacred Mayan ceiba tree, the Buddhist bodhi tree, and the Christmas tree that Joseph Campbell (1974) identifies as such an archetype (of the sacred wisdom-bearing tree, a site of apotheosis) are iconographic, pivotal points of transformation that are now replicated in tree diagrams in computer science, evolutionary phyla (Novacek, 1994; Moser, 1996), and hierarchical theory (Whyte, Wilson and Wilson, 1969; Smith, 1978; Feekes, 1986; Ahl and Allen, 1996). The earth mother, or harvest goddess, transforms into the Gaia of scientific hypothesis (Gadon, 1989). As our cultures evolve, so too do the mythic forms we use to express our existential understandings of ourselves and our relationship to the world around us, from clay pots and golden charms to teleimmersive projections (Cox, 2003). Such archetypal images, together with their symbolic associations, even serve as actors within postmodern critiques of science (Keller and Longino, 1997), such as in a recent debate in evolutionary biology between selfish genes, a view of evolution based in anthrocentric heredity, and the Gaia Hypothesis, a view of evolution grounded in terrestrial balance (Margolis and Sagan, 1986; Barlow, 1991). Even in such contemporary scientific discourse, we find expressed the ancient tensions between humanity and immense, external systems beyond our control or grasp.

The divide between scientific and popular narratives, at the level of story, is not as great as we might suppose. Scientific theories of creation are often viewed as having displaced mythic ones, having more legitimacy because of their foundation of objective inquiry and empirical results (Levi-Strauss, 1963, p. 230; Segal, 1999). In the beginning of

197

the scientific method, academics struggled to rid themselves of crippling subjective folklore (Jaki, 1990; Caudill, 1994). Yet, the Big Bang, one of the most widely accepted scientific theories of creation, can be demonstrated to be a theoretical exercise; its absolute experimental proof is impossible (Adams and Laughlin, 1999; Lakoff and Nunez, 2000). Moreover, in scientific theories of creation of the universe, we find some fascinating parallels with myths (Bierlin, 1994). For example, the role of water in many creation myths is consistent with the scientific primordial soup. If creation myths are widely held beliefs that are impossible to substantiate, then technoscience provides our contemporary creation myths--not in isolation from early myths but in response to them (Jung, 1959). Through the scientific visualizations we circulate, we are perpetuating reinvigorated archetypes, retelling the greatest myths of creation, of life-and-death, the macrocosm and the microcosm, and of our era as part of an ongoing, collective experience.

Visaphoric artforms are valuable documents of our dominant technoscientific culture, but they will inevitably be revised, as with any set of creation myths. They emerge from our groping, our biases, our paradigm shifts, our unities and diversities. Intellectual agnosticism predicts paradigms (such as the Big Bang), but these too are provisional, because science, art, and the humanities are subject to revision. Yet, to say these new accounts are conditional is not to say they are insignificant. Visaphors provide raw material for historical analysis; they are the unsuspecting futures of our following generations' consciousness studies and continuing cultural library. They evince a powerful world view, one of many mythic possibilities.

Appendix List

Donna Cox
Selected List of Publications and Presentations of Scholarship
(or presentations of other forms of creative and performing work)
2000-2007

Publications (chronological by year)

Cox, D. (2000) "Myth Information: Toward a Science of Consciousness"
[Abstract]. *Journal of Consciousness Studies*, 10-15 April 2000, University of
Arizona-Tucson.

Cox, D. (2000) "Visualizing the Virtual Cosmos with Hayden Planetarium and HD
PBS NOVA" and "Creating the Cosmos: Visualization and Remote Virtual
Collaboration." *Proceedings of the Consciousness Reframed 3 Conference*, 24
August 2000, University of Wales College- Newport, pp. 7-8.

Cox, D. (2001) "Creation Myths and Contemporary Science." *Extreme
Parameters: New Dimensions of Interactivity Proceedings*, 11-12 July 2001, La
Universitat Oberta de Catalunya-Barcelona, Spain.

Cox, D. (2002) "Visualization, Media and Mind." *Symposium Proceedings,
Biennale for Electronic Arts in Perth (BEAP) and The 4th International Caiia-Star
Research Conference.* Gallery Exhibition, 31 July-15 September 15 2002, Perth,
Australia (catalogue published).

Cox, D. (2003) "Algorithmic Art, Scientific Visualization, and Tele-immersion:
An Evolving Dialogue with the Universe." In: Malloy, J. ed. *Women, Art, and
Technology.* Cambridge, MA, The MIT Press, pp. 242-259.

Cox, D. (2003) "Metaphorical Vestiges on Info-Viz Trails." Proceedings of the
Consciousness Reframed Conference, 2-5 July 2003, Newport, Wales.

Cox, D., Kindratenko, V., and Pointer, D. (2003) "IntelliBadge(tm) in First
International Workshop on Ubiquitous Systems for Supporting Social Interaction
and Face-to-Face Communication in Public Spaces." *UbiComp*, pp. 41-47.

Cox, D., Kindratenko, V, and Pointer, D. (2003) "IntelliBadge(tm): Towards
Providing Location-Aware Value-Added Services at Academic Conferences." In:
Ed. Dey, A., Schmidt, A. and McCarthy, J. eds. *UbiComp.* Berlin, Springer, pp.
264-280.

Cox, D. (2004) "The Art and Science of Visualization: Metaphorical Maps and
Cultural Models." *Technoetic Arts*, 2:2, pp. 71-79.

Cox, D. (2004) "Visualization in the Life Sciences," In: Subramaniam, S. and
Koslow, S. *Databasing the Brain: Data to Knowledge (Neuroinformatics).*
New York, Wiley, pp. 123-152.

Cox, D. (2005) "Visualizing the Cosmos." In: *INSAP Inspiration of Astronomical Phenomena. Fifth International Conference Proceedings*, 26 June-1 July, 2005, Adler Planetarium, Chicago, IL, pg. 52; invited speaker, Friday, 1 July 2005.

Cox, D. (2006) "Visualization and Visual Metaphors," In: *Aesthetic Computing.* Fishwick, P. ed. Cambridge, MA, The MIT Press, pp. 89-14.

Kähler, R., Cox, D., Patterson, R. Levy, S., Hege, H., and Abel, T. (2002) "Rendering the First Star in the Universe--A Case Study." *Vis2002 Conference Proceedings, IEEE Visualization 2002*, 27 October-1 November 2002, Boston, MA, pp. 537-540.

Betts, A., Cox, D., Dhamankar, R., Kaap, T., Kindratenko, V., Khakshour, A., Leonard, L., Levy, S., Martirano, J., Patterson, R., Pietrowicz, M., Pointer, D., Powell, J., Rajlich, P., Reed, D., Rovedo, A., Sanders, B., Shapiro, M., and Shih, A. (2003) "SC Gets Smart: IntelliBadge™ at SC2002." NCSA Technical Report, January (intellibadge.ncsa.uiuc.edu).

Hall, M.; Betts, A.; Cox, D.; Pointer, D.; Kindratenko, V. (2005) "The Visible Radio: Process Visualization of a Software-Defined Radio," *Visualisation 2005 Proceedings in Print and CD*, 23-28 October 2005, Minneapolis, Minnesota. Alamitos, CA, IEEE Press, pp. 159-165.

Juried Exhibitions:
SIGGRAPH 2000 Animation Festival: "Passport to the Universe," Excerpt from Hayden Planetarium NYC Digital Dome Space Show, Hayden Planetarium, AMNH, August 2000.

SIGGRAPH 2001 Computer Animation Theater: "Evolution of the Universe: Large-scale Structure and Galaxy Formation." HD Animation, Electronic Art and Animation Catalog, published by ACM: New York, August 2001, p. 222. Exhibited at the Los Angeles Convention Center.

DomeFest 2005, three works selected: "Visualization of F3 Tornado within a Supercell Thunderstorm," "Visual Excerpt from *Black Holes: The Other Side of Infinity* (Stellar Orbits Around the Galactic Center Black Hole)," and "Evolution of the Universe: Galaxies Forming on Filamentary Structures." Held at SIGGRAPH 2005; traveled to other planetaria: http://www.domefest.org/, http://access.ncsa.uiuc.edu/Releases/06.09.05_NCSA_Visua.html; http://www.chabotspace.org/domefest/index.htm.
SIGGRAPH 2005 Electronic Theater, 28,000 attendees: "Visualization of an F3 Tornado Within a Simulated Supercell Thunderstorm." Published in SIGGRAPH 2005 Conference Electronic Art and Animation Catalog. Electronic Theater Program, published by ACM SIGGRAPH in conjunction with Computer Graphics World (No. 25, p. 10). Electronic Theater DVD, SIGGRAPH Video Review 150.16 (1 minute, 15 seconds): http://access.ncsa.uiuc.edu/Releases/06.09.05_NCSA_Visua.html.

Invited Exhibitions:
"The Once and Future Web: World's Woven by the Telegraph and Internet," Dr. William Harless, Interactive Drama: http://www.idrama.com/idihome/index.htm. National Library of Medicine, National Institutes of Health, Bethesda, Maryland, May 21-Nov, 2001: http://www.idrama.com/Press/prNLMExhibit.htm

"(art)^n Virtual Visions: three decades of collaboration" Group Show, Papilloma Virus Pschologram (1990), Catalogue No. 28, Brunnier Art Museum, Iowa State University, October 29, 2002 – January 5, 2003.

CALCULART, Exhibit March 9-April 9, 2006: http://www.canvas.uiuc.edu/; http://access.ncsa.uiuc.edu/Briefs/2006-03-10Donna_Cox.html.

Leonardo da Vinci: Man, Inventor, Genius Exhibition, Chicago Museum of Science and Industry, kiosk installation of Cox collaborative digital works (Modern Day Leondardo for emphasis on "observation, synthesis, and invention"). April 14-September 4, 2006: http://www.news.uiuc.edu/news/06/0413leonardo.html.

Multi-Dimensional Imagery: 3D Pixels Realized, Collaborative Artwork by Ellen Sandor (art)^n, Featured Collaborator, Kemper Room Art Gallery, Illinois Institute of Technology, November 9, 2006-January 20, 2007. See *Chicago City Arts Review.*

Presentations:
"Concept, Image, Movement." Interfacing the Future, Plenary Session, Third Annual Digital Arts Symposium, University of Arizona College of Fine Art, April 6-7, 2000, Tucson, AZ.

"Visualizing the Cosmos: Hayden Planetarium Project." Alliance Chautauqua 2000 in Kansas over the Access Grid, August 1, 2000, Lawrence, KS.

"The Necessity for Visual Literacy in Virtual Reality Visualization Research." Keynote speaker, General Session, International Visual Literacy Association Conference, Iowa State University, October 11-14, 2000, Ames, IA.

"The Myth Information in Visualization and Virtual Reality," Stieren Arts Enrichment Series and Trinity University, Stieren Theater, October 30, 2000, San Antonio, TX.

"Structural Symmetries in Myth and Supercomputer Science." Symetries Structurelles Dans le Mythe et les Supercalculateurs," "L'Art a L'ere Post-Biologique, Ecole Nationale Superieure des Beaux-Arts, December 12, 2000, Paris, France.

"Myth Information," E-naissance: New Configurations of Mind, Body, and Space Conference, Galleria D'arte Moderna e Contemporanea di Torino (GAM), Supported by the Fondazione Fitzcarraldo, Caiia-Star Public Symposium, March 28, 2001, Turin, Italy

"Renaissance Teams, Visualization, and Virtual Reality," General Public Presentation at the Hayden Planetarium, American Museum of Natural History, June 28, 2001, New York City.

"Visual Metaphors for Tracking People: Visualization and IntelliBadge." Symposium Proceedings, Nomadic Transitions/ Thinking about Art, Hochschule fur Gestaltung und Kunst (University of Art and Design). Conference Proceedings and Abstracts Published by Kongress-Themen und Zusammenfassungen, pp. 3, 63. April 10-12, 2003, Zurich, Switzerland.

"Beyond Computing: The Search for Creativity," Keynote for SC2003 Conference: Igniting Innovation, November 18, 2003, Phoenix, Arizona, November 18, 2003. 3000 attendees at keynote.

"Visualization and Visual Metaphors," Plenary Session April 29, 2004, El Congreso Internacional, "Desafios para la Identidad Ubicua" Celebrado at Cibe@art-Bilbao, Festival Ciberart-Bilbao, April 26-29, 2004, Bilbao, Spain.

"CyberOutreach: Designing Scientific Data for Non-expert Audiences." Keynote, TeraGrid Conference. June 14, 2006.

"CyberOutreach: Non-Expert Audiences and the Design of Scientific Data." Initiative in Innovative Computing at Harvard Distinguished Seminar Series, Harvard University, October 16, 2006, Boston, MA.

Panel Presentations
"Visualizing the Cosmos: Smoke or Mirrors" SIGGRAPH 2000 Conference, panel chair and participant, published abstract in the SIGGRAPH 2000 Program and Buyer's Guide, page 44, published by the ACM SIGGRAPH 2000, 27th International Conference on Computer Graphics and Interactive Techniques, Ernest Morial Convention Center, July 25-27, 2000, New Orleans, LA.

"The Art of Scientific Visualization, Data Representation, and Renaissance Teams," Informatics Seminar, April 26, 2001, University of Illinois at Chicago.

"The CAVE and Beyond: VR Art in Museums and Galleries," SIGGRAPH, August 15, 2001, Los Angeles, CA.

"Metaphoric Mappings," and "Emergent Systems," presentation in round table sessions, UC DARNet 9/11 - N2: Art, Science & Technology in Times of Crisis Conference, UC Digital Arts Research Network, Tuesday, Nov. 13, 2001, University of California at Irvine and Thursday, Nov. 8, 2001 UC at Santa Cruz.

"Universe" remote virtual collaboration demonstration between the Stephen Hawking Lab at Cambridge University, UK and UCSD, presented on a stereo interactive display, iGrid 2002, Sept. 23-26 2002, Amsterdam, Nederland,

"Streaming Super High Definition Video from Chicago to Los Angeles over Internet2 Backbone" Abilene Internet 2 Fall Members Meeting, demonstration and

presentation (provided ultra-high resolution visualizations at 3840x2048resolution and streamed from Chicago over high-speed internet to the University of Southern California Zemekis Theater), October 28-30, 2002.

"Visualizing the Global: Computer Modeling, Ecology, Politics," panelist and organizer, October 16, 2003, Beckman Institute, University of Illinois.

"The Moving Image: What Do We Learn from Simulations, Modeling, and Animation," Image and Meaning (IM2) Workshop, June 23, 2005, Getty Museum, Los Angeles, CA.

Streaming Video and International Real-Time 4K Digital Cinema, iGrid2005, September 25-30, 2005, San Diego, CA.

"Visualizing Scientific Information: The Mixture of Science and Art." Association of American Universities (AAU), October 11, 2005, Champaign, IL.

"Chew on This: A Trillion Bytes for All Science and Engineering", Designing Data for Public Outreach." American Association for the Advancement of Science, Friday, February 16, 2007, San Francisco, CA.

SPITZ

November 25, 2008

Professor Donna Cox
Director, Advanced Visualization Laboratory
National Center for Supercomputing Applications
1205 W. Clark St, Room 2034
Urbana, IL 61801

Dear Donna,

I wanted to give you a quick update on "Black Holes: the Other Side of Infinity" and let you know that it continues to be a strong performer. Since its launch at Denver's Gates Planetarium in Spring 2006, we have licensed "Black Holes" to more than 50 theaters around the world, making it one of the most widely distributed shows of the past few years. To date, "Black Holes" has been translated into seven languages (with more to come) and has been seen by an estimated 1.4 million viewers.

These numbers will continue to grow as the show is picked up by new venues seeking high-quality content. Approximately 100 new fulldome theaters are opening every year, and all are looking for shows that will drive attendance and generate buzz - "Black Holes" certainly does both! Recent launches include the Einstein Planetarium at the National Air & Space Museum in D.C. and the newly refurbished Cosmonova at the Swedish Museum of Natural History in Stockholm.

Please extend my thanks to your entire team for helping to make "Black Holes: the Other Side of Infinity" such a success, and best of luck on your next project.

Sincerely,

Mike Bruno
Creative Media Director
Spitz Fulldome Show Distribution

SPITZ, INC
P.O. Box 198
700 Brandywine Drive
Chadds Ford, PA 19317
Tel   610.459.5200
Fax   610.459.3830
Email spitz@spitzinc.com

Thomas Lucas Productions, Inc.

November 4, 2008

Professor Donna Cox
National Center for Supercomputing Applications
University of Illinois
1205 West Clark Street
Urbana, Illinois 61801

Dear Donna,

I am writing to summarize my working relationship with you over the years.

I first approached you in 1996 to contribute to a major three-part television series we produced for the U.S. Public Broadcasting Service (PBS) titled "Mysteries of Deep Space." I had seen your work on the IMAX film "Cosmic Voyage" and saw that you and your team had developed techniques for visualizing scientific data at a level of detail and quality I had not seen before.

Our collaboration has continued through nine productions since. Among the early highlights was the highly successful PBS program "Runaway Universe." It was the first high-profile American science special to be produced in high-definition video. It featured a range of unique accomplishments in scientific visualization, including flights through accurate 3D maps of the local region of the universe extending out to a distance of 300 million light years.

On many of our productions, you and your team have played a roll that goes far beyond simply producing visualizations. As an example, your work on "Hunt for the Supertwister" for PBS and the BBC took viewers inside a groundbreaking thunderstorm simulation. Your team aided scientists in their quest to understand the "trigger" for a tornado by mining the data, then visualizing the "micro-events" thought to be responsible.

Our most recent collaboration included a series of programs exploring the cosmic dark side: black holes. They include an ultra-high resolution full-dome planetarium show, an educational film for the National Science Foundation, and two prime-time television specials -- each exploring the workings of Nature's strangest and most extreme realms.

In these programs, your visualizations have reached new heights of drama and aesthetics. For the first time, they are giving millions of people a glimpse of the processes that shape our universe. They are also exposing viewers to the results of large-scale computer studies, now considered a major branch of scientific investigation.

I know of no other team anywhere in the world that has worked at such a consistently high level to visualize science for public presentation. Part of your success, I believe, is that you have built a team of artists and programmers who are steeped in science. In addition, you have used your successes to gain a high degree of support from your university. Your ability to marshal visualization and computational resources has led to collaborations on a global scale.

Another reason for your success is your ability to master new technologies, from large screen IMAX and digital planetarium image production to stereoscopic techniques. Together, we are now about to launch a new full-dome production about the climate in collaboration with the California Academy of Sciences. We are also planning to move into producing a series of films for 3D digital cinemas now being built in science centers and museums around the world.

Best regards,

Thomas Lucas
Producer/Director

UNIVERSITY OF CALIFORNIA, SAN DIEGO

UCSD

CENTER FOR ASTROPHYSICS AND SPACE SCIENCES (CASS)
9500 GILMAN DRIVE #0424
LA JOLLA, CA 92093-0424

PROFESSOR MICHAEL NORMAN
PHONE: (858) 822-4194
MLNORMAN@UCSD.EDU

December 19, 2008

Professor Donna Cox
National Center for Supercomputing Applications
and School of Art and Design
University of Illinois at Urbana-Champaign

Dear Donna;

I am delighted and honored to write a letter of support for your Ph. D. dissertation. Since we began collaborating on scientific visualizations in astrophysics and cosmology 22 years ago, your work has been the most faithful to the science, the most ambitious in its conception and execution, and the most beautiful to behold of any that I know of. I have found our many projects to be stimulating and rewarding, but I am particularly impressed with the vision and passion you have brought to them. As a scientist, I view your productions as no less than the cultural artifacts of our time, depicting the state of scientific knowledge about the universe using the best and most appropriate means of expression: computer animation. For we live in a dynamic, complex, and beautiful universe, and what better way to convey that than with state-of-the-art computer animation?

Our collaborative visualization projects have helped me extract scientific understanding from unfathomable piles of supercomputer simulation data. As I reflect on the projects we have done together, I see a record of my own trajectory as a computational astrophysicist as well. I have been driven by the need to *see* the predictions of physical theories about our universe. This began with our 1987 SIGGRAPH Film and Video Show entry *"Astrophysical Jet"*, which for me revealed the subtle details of two-dimensional fluid dynamics encoded in the Euler equations. As the scope, scale, and complexity of my simulations grew, so did our scientific visualizations. These have been particularly valuable for better understanding the output of my cosmological simulations, which are not only three-dimensional and dynamic, but also span a large range of spatial scales. There are basically no tools for visualizing the results of such simulations, and therefore the work we did on *"Runaway Universe"* (on galaxy formation) and *"Monster of the Milky Way"* (on the first stars) were particularly insightful.

The techniques you and your Renaissance Team have developed for animating and traversing multi-scale data from my cosmological adaptive mesh refinement simulations are highly innovative, and produce the most artifact-free renderings of the data that I am aware of. Your recent animations on the formation of the Milky Way revealed new details about hierarchical structure formation not previously appreciated by me or other scientists regarding the dynamics of gaseous disks. These discoveries, made through scientific visualization, are motivating a Ph. D. thesis project of one of my current graduate students.

Beside their scientific value, your scientific visualizations have been a wonderful tool to inform the public about the universe around them. I personally have been highly motivated by the fact that our projects will reach a large audience through film, television, and planetarium sky shows. I am delighted by the fact that our visualization of the formation of galaxies has been seen by millions of children and adults in the Big

Page 1 of 2

211

Bang Bowl at the Hayden Planetarium, NYC. Our collaborations have wonderfully realized a goal we share, which is reaching a larger audience with our science and art.

Finally, I would like to recognize the importance of the Renaissance Team concept which you pioneered at Illinois lo these many years ago, and have nurtured so beautifully over the years. Yours is the only group I am aware of that has worked exclusively with computational scientists over so many years and in such a wide array of disciplines. The corpus of your creative work is a testament to the genius of this idea, as it has brought us the best and most beautiful exemplars of scientific communication. I am thinking here not of my own work, but the spectacular visualizations of thunderstorm dynamics with Prof. Bob Wilhelmson.

Only a powerful, sustaining vision such as yours could have made this happen despite the challenges of life and funding. You have realized this vision, and of that you should be very proud. I feel privileged to have come into the orbit of your vision and experienced the creativity of your Renaissance Team on more than one occasion. I wish you the best completing your Ph. D. dissertation.

Sincerely yours,

Michael L. Norman
Distinguished Professor of Physics
Director, Laboratory for Computational Astrophysics
Chief Scientific Officer
San Diego Supercomputer Center

MICHIGAN STATE
U N I V E R S I T Y

December 5, 2008

Dear Donna,

I have collaborated with you and your group for more than a decade, starting when I was an undergraduate astrophysics student working with Professor Michael Norman at the National Center for Supercomputing Applications, and continuing through today, where I find myself an assistant professor in the Department of Physics and Astronomy at Michigan State University. My area of expertise is the use of large-scale simulations of cosmological structure, which includes the formation and evolution of stars, galaxies, and the web of gaseous filaments that connects these structures. Over the more than a decade that we have known each other, we have collaborated on many projects to visualize simulations of these phenomena, in ways that are useful for both domain experts (that is, astrophysicists) and laypersons alike. You and your research group at the National Center for Supercomputing Applications have been incredibly innovative in the ways that you visualize my simulations, and have enabled me to discover new things in my data that I would not otherwise have seen were it not for our collaboration. For example, your visualization of my simulation exploring the formation of a Milky Way-sized galaxy vastly increased my understanding of how "hierarchical structure formation" - that is, the formation of larger galaxies by the merger and accretion of smaller galaxies - takes place, and clarified that there are two different fundamental mechanisms by which galaxies acquire their mass. This increase in my understanding would have taken much longer if not for your group's work.

Brian O'Shea
Assistant Professor, Physics

Physics & Astronomy
Department
Michigan State University
Room 3255
Biomedical Physical Sciences
East Lansing, Michigan
48824-2320

☎: (517) 884-5638
FAX: (517) 353-4500

http://www.pa.msu.edu/~oshea/

MSU is an affirmative-action,
equal-opportunity institution.

I would also like to comment on your group's visualization of scientific data sets as a means of conveying information to non-expert audiences. As a scientist at a public institution, whose research funding comes from public sources, I feel that I have an obligation to explain the meaning and value of my work to the public. When one is considering a subject as esoteric as astrophysics, which deals with scales measured in light-years and eons, this can often be an incredibly difficult task. As a result, your visualizations of my work (and the work of other astronomers and astrophysicists) have been an extremely useful way of conveying meaning. Through our collaboration, you have created visualizations of my simulations that manage to convey a tremendous amount of information while still being true to the detailed, technical meaning of the calculations. I think that this is due in large part to the "Renaissance team" that you have created at UIUC, which combines artists and programmers in a closely-knit group that encourages deep interaction and synergy between people with a diverse range of talents, and which has resulted in the creation of sophisticated tools that enable you to visualize data in unprecedented ways. These unique visualizations have been shown on television and in internationally-known museums, including the Adler Planetarium in Chicago and the Hayden Planetarium at the American Museum of
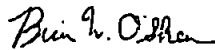
213

Natural History in New York City, and have touched the lives of millions of people that otherwise never would have been aware of the research done by myself and other computational scientists. To the best of my knowledge, you and your team are the only group that works in such close, extended collaborations with scientists in a broad range of disciplines, which is one of the many reasons that you are so well-respected in the scientific outreach community.

In summary, I think that the work that you and your team at the University of Illinois are doing is novel, and results from your creation of a "Renaissance team" of artists and programmers that has extended, deep collaborations with computational scientists in a range of disciplines. These collaborations have enabled myself and other scientists to explore their data in unique and otherwise-impossible ways, and allows the presentation of esoteric concepts to the public in an easily accessible way. I enthusiastically support your receipt of a doctoral degree, and look forward to seeing the results of our future endeavors together!

Sincerely,

Dr. Brian W. O'Shea
Professor
Michigan State University

SPITZ
An EAS Company

"Black Holes: The Other Side of Infinity"

Venues as of October 20, 2008

Venue	Location	System	Year
Thronateeska Heritage Center*	Albany, Georgia	SciDome	2008
Lodestar Astronomy Center	Albuquerque, NM	DigitalSky	2006
University of Michigan	Ann Arbor, MI	Elumens	2007
Antioch Unified School District	Antioch, CA	Elumens	2007
Eugenides Foundation	Athens, Greece	Digistar3	2006
Kern Community College District	Bakersfield, CA	SciDome	2007
Haydar Aliev Science Center	Baku, Azerbaijan	Digitalis	2008
Louisiana Arts & Science Museum	Baton Rouge, LA	DigitalSky	2006
Torre del Sole	Brambati di Sopra, Italy	Scidome	2008
Adler Planetarium	Chicago IL	Digistar3	2007
De Anza College	Cupertino, CA	DigitalSky	2007
Korea National Science Museum*	Daejon, Korea	SkyVision	2008
Denver Museum of Nature & Science	Denver, CO	Global Immersion	2006
Elizabeth School District	Elizabeth, NJ	Digitalis	2006
Santa Fe Community College	Gainesville, FL	SciDome	2007
Grambling State University*	Grambling, LA	SciDome	2008
Greenwich Royal Observatory	Greenwich, UK	Digistar3	2007
State Museum of Pennsylvania	Harrisburg, PA	SciDome	2006
James Madison University	Harrisonburg, VA	Digistar3	2008
Catawba Science Center	Hickory, NC	Mediaglobe2	2007
Imiloa Astronomy Center	Hilo, HI	Digistar3	2008
Lambuth University	Jackson, TN	Digitalis	2008
Sternenturm Judenburg	Judenburg, Austria	Zeiss Powerdome	2008
Lebanon Valley School District	Lebanon, PA	SciDome	2008
Aerospace Education Center	Little Rock, AK	Eskyll	2007
Mansfield University of PA	Mansfield, PA	SciDome	2008
Heritage Planetarium	Maryville, TN	Mediaglobe	2006
Mesquite Independent School District	Mesquite, TX	SciDome	2008
Instituto Politecnico Nacional	Mexico City, Mexico	Digistar3	2007
Milwaukee Public Museum	Milwaukee, WI	Digistar3	2007
New Rochelle School District	New Rochelle, NY	SciDome	2007
Clarkstown School District	Nyack, NY	SciDome	2006
Chabot Space Science Center	Oakland, CA	DigitalSky	2007
Utah Valley State College	Orem, UT	SciDome	2007
SpaceTime Astronomy	Perth, Australia	Mirrordome	2007
Oregon Museum of Science & Industry	Portland, OR	Digistar3	2007
University of Rhode Island	Providence, RI	Digistar3sp	2007
Reading Public Museum	Reading, PA	SciDome	2007
Sacramento State University	Sacramento, CA	Digistar3	2009
College of San Mateo	San Mateo, CA	Digistar3sp	2007
Zeiss/Schwaz Planetarium	Schwaz-Tyrol, Austria	Zeiss Powerdome	2008
Learning Technologies	Somerville, MA	Digital Starlab	2008
Eastern University	St. Davids, PA	SciDome	2006
Cosmonova	Stockholm, Sweden	Global Immersion	2008
Dolphinarium and Planetarium	Tampere, Finland	Custom	2006
Thessaloniki Science Center	Thessaloniki, Greece	RSA Cosmos	2006

Spitz, Inc. US Route One, Chadds Ford, PA 19317

Manten "Sunshine" Planetarium	Tokyo, Japan	SkyVision	2009
Einstein Planetarium, NASM	Washington, DC	DigitalSky	2008
INTECH	Winchester, UK	Global Immersion	2008
Young Harris College	Young Harris, GA	DigitalSky	2008
Youngstown State University	Youngstown, OH	SciDome	2008

Spitz, Inc. US Route One, Chadds Ford, PA 19317

MULTIMEDIA RESEARCH

33 BROWNS LANE • BELLPORT, NY 11713 • (631) 286-8925

Black Holes: The Other Side of Infinity
Summative Evaluation of
Planetarium Film with Adults and Teens

Report for
Denver Museum of Nature and Science

by
Barbara N. Flagg, Ed.D.
Multimedia Research

with assistance of
Genah Burditt
Susan Henningsen

Research Report No. 06-006
June 16, 2006

TABLE OF CONTENTS

ii

218

EXECUTIVE SUMMARY
SUMMATIVE EVALUATION OF *BLACK HOLES* WITH ADULTS AND TEENS
MULTIMEDIA RESEARCH, JUNE 16, 2006

With support from the National Science Foundation, Denver Museum of Nature and Science and Thomas Lucas Productions have produced a planetarium film entitled, *Black Holes: The Other Side of Infinity*. The 20-minute full-motion program uses scientific simulations and data-based animations to illustrate the death of stars and the birth and characteristics of black holes. The summative evaluation focused on appeal to and impact on adult and teen museum visitors.

Method
A quasi-experimental separate-sample pretest/posttest design was used to evaluate the film in its natural theater setting. A random sample of 126 adults and teens completed questionnaires prior to viewing the film and a different random sample of 142 completed questionnaires after viewing. The pre and post viewing groups did not differ significantly on classification variables of gender, ethnicity, age group, education and number of planetarium films ever seen. A small subset volunteered to answer follow-up questions via email one week after their planetarium visit.

Appeal
The most positive aspects of the film according to most (45%) respondents are the animation, visuals and graphics. Another 35% like best the informative quality of the film. Smaller portions of the sample like the clear and interesting explanations (15%); the experiential quality (13%); narration (9%); and colors (8%). On the other hand, respondents feel the film is too short (21%); confusing (15%); or lacking in information (11%).

Comprehension
Open-ended response questions reveal that viewing the planetarium film significantly improves understanding of what a black hole is and how scientists know that black holes exist. In addition, a true-false test indicates that viewers learn other specifics about black holes; for example, that black holes are not dark inside and that our galaxy has a supermassive black hole at its center.

Subsequent Activity
Of viewers contacted via email one week after their visit, 71% had recommended the film to others, 10% had read, seen or heard something in other media that relates to black holes and 3% had visited a website related to black holes.

In conclusion, the summative evaluation shows that *Black Holes: The Other Side of Infinity* successfully both entertains and educates adults and teens.

iii

INTRODUCTION

With support from the National Science Foundation, Denver Museum of Nature and Science and Thomas Lucas Productions have produced a planetarium film entitled, *Black Holes: The Other Side of Infinity*. The 20-minute full-motion program uses scientific simulations and data-based animations to illustrate the death of stars and the birth and characteristics of black holes.

The summative evaluation reported here focuses on the following major outcomes:

- To what extent and in what ways did the film appeal to viewers?
- To what extent did the film achieve its intended viewing goals?
- Did viewing the film influence the audience beyond the museum visit?

METHOD

Research Design

A quasi-experimental separate-sample pretest/posttest design was used to evaluate the film in its natural theater setting. Over a period of three days at the Denver Museum of Nature and Science, researchers recruited random viewers older than 12 years and stratified by gender. A random sample completed questionnaires prior to viewing the film and a different random sample was surveyed after viewing. A small subset of the samples volunteered to answer follow-up questions via email one week after seeing the film. Several characteristics of the population and treatment (i.e., the planetarium film) led to the decision to use this research design.

First, the population to which we wish to generalize are self-selected museum visitors whose intention is to view a planetarium film. Locating an equivalent control group who would not view the film is virtually impossible. There are no comparable museum visitors from whom the treatment (the film) could be withheld. The best control group is a sample of museum visitors who intend to view the film but have not yet done so.

Secondly, we cannot assume that the scientifically predisposed museum visitors would be unfamiliar with the film content, thus it is important to include a pretest that establishes what the audience knows prior to seeing the film. Pretesting and posttesting the same sample, however, is not an acceptable procedure, because the pretest given just prior to viewing sensitizes the audience to the content of the film and affects their posttest results. The separate-sample design controls for the main and interactive effects of testing. One group is tested prior to seeing the film and a randomized equivalent group tested after seeing the film.

Third, random sampling is logistically simple in the theater environment where the audience lines up before showtime. Randomization is used to eliminate systematic bias between the pre-viewing sample and the post-viewing sample. As argued by Campbell and Stanley (1963), "the most adequate all-purpose assurance of lack of initial biases between groups is randomization"

(p. 25). In this evaluation, because of limited numbers lining up in the preshow area within 15 minutes of showtime, a stratified systematic random sampling procedure is used. This means that the first male and first female respondent is selected through the use of a random number between 1 and 5 (using a random-number table) and then every second male and female after that first random person is also recruited.

Finally, the drawbacks of this research design, in general, are its failure to control for history, maturation, mortality and the interaction of these. However, in this specific case, where the film treatment is only 25 minutes long and the audience is captive, there is little chance of changes in groups due to history, maturation, or mortality; thus, these are non-issues for this evaluation.

In conclusion, the separate-sample pretest-posttest design is considered the strongest approach for evaluating the planetarium film in the natural theater setting with a random sampling of the population of viewers.

Procedure

During a non-holiday period of Friday-Sunday in April, 2006, the sample was recruited from visitors, 13 and older, as they lined up for the film at the Gates Planetarium, Denver Museum of Nature and Science. The recruitment for the previewing sample alternated with recruitment for the postviewing sample over the course of 31 shows. Typically excluded from recruitment were school groups, single adults accompanied by children below the age of five and adults who were part of a group of five or more. As ticket holders lined up for the show, a random number determined who was first approached for recruitment; thereafter every second male and female was recruited. All visitors were offered a free IMAX theater ticket in return for completing a previewing or postviewing questionnaire. The previewing respondents completed the ten-minute questionnaire on clipboards while standing in line. The postviewing respondents were provided with colorful leis to help identify them in the exiting crowd and completed the fifteen-minute questionnaire at tables set up near the exit door.

Questionnaires

Draft questionnaires were twice pilot tested over two weekends with a total of 56 adults and teens, assessing readability, length, clarity and feedback on phrasing of true-false statements.

Demographic and Background Variables. Both the pre-viewing and post-viewing questionnaires established respondents' status with respect to five classification variables: gender, age group, ethnicity, education, number of planetarium films ever seen.

Film Appeal. Postviewing respondents rated film appeal on a variety of descriptors and explained what they liked and did not like about the film and why.

Film Knowledge. Postviewing respondents rated the film's clarity of presentation and influence on knowledge. Both the previewing and postviewing questionnaires included a knowledge test to assess understanding of film content: two open-ended questions (as best you can, explain what

a black hole is and how scientists know that black holes exist) and ten "true-false-don't know" questions, as follows:

Influence of the film beyond the museum visit. Emailed questions, one week later, asked
(1) Did you recommend the show to anyone - family, friend, colleague? If so, what did you say about it?
(2) Since seeing the show, have you visited any websites related to black holes?
(3) Since seeing the show, have you read, seen or heard anything in OTHER MEDIA that relates to black holes?
(4) Have you taken any other actions that relate to seeing the "Black Holes" film?

Sample

Three researchers recruited over a non-holiday period of 1 weekday and 2 weekend days during 9 weekday shows and 22 weekend shows. Weekend respondents represented 83% of the final sample. The total number of usable questionnaires (N=268) included 126 previewing question-naires and 142 postviewing questionnaires. Information from demographic and background questions was used to determine whether the two independent samples (pre and post) should be looked at as having come from the same population. Chi-square analyses revealed that the pre and post viewing groups did not differ significantly with respect to the classifications of gender, ethnicity, age group, education, and the number of planetarium films ever seen. The distribution of the sample on these classification variables is presented in Table 1 on the next page.

The sample, as planned, includes equal gender distribution, 21% teen and 24% minority repre-sentation. Colorado's census statistics indicate 25% minority population and 35% in Denver. Of our adult sample, 55% are college graduates compared with 33% in the Colorado population and 35% in Denver. One-fifth of the respondents were seeing their first planetarium film, and 29% were very experienced viewers, having seen four or more shows.

Table 1. Demographic and background variables (N = 268)

Variable	Categories	Percent
Gender	Female	50%
	Male	50%
Ethnicity	White	76%
	Minority	24%
Age Group	Teens	21%
Teen: Range = 13-19; Mean = 16	Adults	79%
Adult: Range = 20-82; Mean = 40		
Education	Currently in grade __	16%
	Completed HS or less	12%
	Some college	27%
	College graduate	21%
	Post graduate	23%
Number of planetarium shows ever seen	This is my first show.	21%
	One other show.	18%
	2-3 other shows	32%
	Four or more shows.	29%

222

Follow-up sample. Of the 213 adult respondents, 121 (57%) volunteered legible email addresses for a week-later follow-up contact. Volunteers were emailed the following questions: 1. Did you recommend the show to anyone - family, friend, colleague? If so, what did you say about it? 2. Since seeing the show, have you visited any websites related to black holes? 3. Since seeing the show, have you read, seen or heard anything in OTHER MEDIA that relates to black holes? 4. Have you taken any other actions that relate to seeing the "Black Holes" film? Of the 121 volunteers, 31 (26%) responded within two weeks of the email request. This sub-sample is representative of the full sample's demographics except that the sub-sample includes 65% females.

Data Analysis

Chi-square, Fisher's Exact tests and two-sample t-tests are used where appropriate for statistical analysis. All relationships are analyzed for statistical significance, which is reported if p values are less than .05. Variables explored include grade and gender. Qualitative responses are sorted and analyzed by keyword and key phrase.

RESULTS: APPEAL

Quantitative Ratings

After viewing *Black Holes: The Other Side of Infinity*, respondents rated on a scale of 1 to 7 certain entertainment qualities of the show. Table 2 below presents the mean ratings for the film for each pair of descriptions, in the order presented in the questionnaire.

Respondents were quite positive about the overall entertainment value of the film. There were no sub-sample rating differences for age group, gender, ethnicity or educational background. However, frequency of exposure to planetarium shows significantly influenced the ratings: Those who had only seen this show and/or one other planetarium show gave significantly higher ratings on all the descriptors compared with those who had seen two or more other shows.

Table 2. Appeal ratings of film

	1	2	3	4	5	6	7	
Disliked the show						6.1		Liked the show
Visually dull						6.4		Visually exciting
Boring story					5.7			Engaging story
Decreased my curiosity						6.0		Increased my curiosity
Will not recommend						6.1		Will recommend

What was Liked about Film

In an open-ended question, viewers were asked what they liked about the *Black Holes: The Other Side of Infinity* and why. Table 3 below presents the major categories of what viewers liked most, in order of most to least frequently mentioned categories for the sample.

The majority (45%) of respondents focused on graphics, animation or visuals as the most positive aspect of the video. Another 35% liked best the informative quality of the film. Smaller portions of the sample liked that the explanation was clear (15%), the experiential quality (13%), the narration (9%), the colors (8%) and the section on Einstein and space-time (5%).

Table 3. What viewers liked about *Black Holes*[1]

Categories	%	Examples of Responses
Graphics, Animation, Visuals	45%	• I really liked all of the visual explanations of Super Novas and their black holes. I am a visual learner so it was very interesting. • The graphics were good. • The visual effects, very cool to watch. • The visuals were spectacular. • Great animation; graphics.
Informative	35%	• Informative on a difficult subject. • Makes you think and discover new ideas. • Informational, widened my knowledge of Milky Way • Everything was very informative, it is interesting to know how they were formed.
Explanation clear, interesting	15%	• Explained a complex issue about as well as possible. • Simple explanation of what we were looking at. • Very interesting. • Concise presentation.
Experiential quality	13%	• I liked how it felt like you were there. • It made you feel in it. • I felt like I was really there.
Narration	9%	• Narration excellent. • Good narration.
Colors	8%	• I like the colors because they were cool. • It was very beautiful, I loved the colors.
Einstein Space-Time section	5%	• I liked how they compared it to the way Einstein saw a black hole as a fabric of time. • Very much liked the visual representation of Einstein's theories. I had never been able to really understand the 'meat and potatoes' of space-time. • The explanation of Einstein's time/space theory. I had not thought about it in regards to black holes before.

---

[1] Percentages have been rounded off and add up to more than 100% because viewers listed more than one category liked.

What was Not Liked about Film

Table 4 presents categories of what viewers did not like about *Black Holes: The Other Side of Infinity*. One-fifth of viewers like all of the film; another fifth felt it was too short. Smaller portions of the audience felt confused by the film (15%), wanted more information (11%) or disliked part of the physical experience of the planetarium (10%).

Table 4. What viewers did not like about *Black Holes*[2]

Categories	%	Examples of Responses
Liked it all	21%	
Too short	21%	• It was too short. • The program felt too short, abrupt, especially for the price.
Confusing	15%	• There was not a good definition of a black hole; that is, one I can relate to. • Wormhole not clear. • I got lost around the time of the wormhole and had a hard time distinguishing between what was scientific fact and what was a hypothesis. • The part where they were explaining bending space and where they showed the picture of Einstein was kind of hard to understand. • Just seeing the lights of black hole didn't give me a big picture. Maybe labels? • No points of reference after our galaxy.
Still have questions; want more information	11%	• Wanted to know a bit more, cold add more explanation partly about Einstein's theory and what scientists think now. • Could have explained a little bit more about Hawaii work. • Needed more on how black holes are being studied. • Not much new information was given. I already knew a lot of it. • Ending very abrupt – leaves a lot of questions open. • I didn't like how there was not closure at the end of the show. I felt like in the end it is all still "theory" and a lot is still to be proved.
Physical space, experience	10%	• My neck aches a bit from trying to look up and back in the seats. • My seat. • Made me a little sick feeling. • Music was too loud It made me jump.

[2] Percentages have been rounded off and add up to more than 100% because viewers listed more than one category not liked.

RESULTS: COMPREHENSION

Quantitative Ratings

After viewing *Black Holes: The Other Side of Infinity*, respondents rated on a scale of 1 to 7 certain content qualities of the show. Table 5 below presents the mean ratings for the film for each pair of descriptions. Respondents were moderately positive about comprehension of the film content. There were no sub-sample rating differences for age group, gender, ethnicity or educational background. However, frequency of exposure to planetarium shows significantly influenced the ratings: Those who had only seen this show and/or one other planetarium show gave significantly higher ratings on both descriptors compared with those who had seen two or more other shows.

Table 5. Comprehension ratings of film

	1	2	3	4	5	6	7	
Confusing presentation					5.6			Clear presentation
Learned nothing					5.5			Learned a lot

Impact on Knowledge

Recall of main content points as presented in *Black Holes: The Other Side of Infinity* was assessed via two open-ended questions and a 10-point True-False-Don't Know test.

What is a black hole? Participants explained as best they could what a black hole is. In order to assess whether those who had seen the film gave responses with better accuracy and fewer misconceptions than those who had not experienced the show, answers were first coded dichotomously according to six content categories in Table 6 below. Two response examples are given under each category. The percent of responses in each category is given for the pre-viewing sample (column 2) and the post-viewing sample (column 3). Significant Fisher exact tests are indicated in column 3 for the whole sample and columns 4-9 for sub-samples. Significance (SIG) means that the frequency of the category for previewing and postviewing respondents differed beyond chance; for example, in row 3, column 9, minorities who had viewed the film were more likely than minorities who had not seen the film to respond that black holes are a puncture in space-time.

Table 6. Response categories for what a black hole is

1	2	3	4	5	6	7	8	9
Category for what a black hole is	All Pre	All Post	Adult	Teen	Female	Male	White	Mi-nority
A star dies, implodes, collapses, goes supernova, remnants of dead star; e.g., End product of a dead star: Remnant of supernova; collapsed core of star.	31%	54% SIG	SIG	-	SIG	-	SIG	-
A puncture, hole or dent in space-time; A hole in space-time. A rip in the fabric of space-time...	1%	13% SIG	SIG	-	SIG	SIG	SIG	SIG
Immense gravity, enormous gravita-tional pull, gravity to the max; e.g., Gravity to the max. A massive force of gravity that forces every-thing into it.	20%	25%	-	-	SIG	-	-	-
Light, matter cannot escape; e.g., A place in space where nothing, not even light, can escape it. Nothing escapes black holes, not even light.	22% SIG	11%	SIG	-	-	SIG	-	SIG
Very dense, matter packed densely, massive concentration of matter; e.g., An area of extremely dense space... Point of incredible density...	16%	10%	-	-	-	-	-	-
A singularity, e.g.; A singularity in space... ...resulting in an infinitely small singularity.	5%	4%	-	-	-	-	-	-

Prior to seeing the film, respondents were most likely to write that black holes are the result of a collapsed star (31%); significantly more respondents (54%) described black holes in this way after seeing the film. The film also showed a significant influence on viewers' likelihood to de-scribe a black hole as a puncture in space-time (1% pre vs. 13% post).

Similar percentages of respondents both before and after seeing the film described black holes as having immense gravity, extreme density, and a singularity. After seeing the film, significantly fewer respondents wrote that light or matter can not escape a black hole (22% pre vs. 11% post).

Sub-samples. After the planetarium experience, females were significantly more likely to point out that black holes are the result of a dying star, that they puncture space-time and have enor-mous gravitational pull. After seeing the show, males and minority respondents were signifi-cantly more likely to write that black holes are a hole in space-time and less likely to write about light not escaping a black hole.

To explore quantitative differences in understanding of what a black hole is, responses scored based on their correctness and number of ideas provided: Correct includes two or more correct ideas with no inaccuracies (3 points); Mostly correct includes two correct ideas but may include additional inaccurate statements (2 pts); Partially correct includes one correct idea but may in-clude inaccurate statements (1 pt).

228

The mean achievement score after seeing the film is 1.2 for the postviewing sample, significantly higher than the mean score of 0.9 for the previewing sample.[3] Viewing the planetarium show significantly increased understanding of what a black hole is for the sub-sample of females (pre= 0.4 vs. post = 1.1) but not for teens, males or minorities.

How do scientists know that black holes exist? Participants explained as best they could how scientists know black holes exist. In order to assess whether those who had seen the film gave responses with better accuracy and fewer misconceptions than those who had not experienced the show, answers were coded dichotomously according to categories in Table 7 below. Eight categories of varying levels of correctness were applied to responses. Two response examples are given under each category. The percent of responses in each category is given for the pre-viewing sample (column 2) and the post-viewing sample (column 3). Significant Fisher exact tests are indicated in column 3 for the whole sample and columns 4-9 for sub-samples. Significance (SIG) means that the frequency of the category for previewing and postviewing respondents differed beyond chance; for example, in row 1, column 6, females who had viewed the film were more likely than females who had not seen the film to respond that scientists know black holes exist because of their effect on motions of stars.

---

[3] Two sample t - test, $p < .01$.

Table 7. Response categories for how scientists know that a black hole exists

Category for how scientists know a black holes exist	All Pre	All Post	Adult	Teen	Female	Male	White	Minority
Effect on environment, motions of stars; e.g., They can see stars are being thrusted quickly into orbit around the center of our galaxy. By using telescopes they can see stars orbiting around the hole.	4%	29% SIG	SIG	-	SIG	SIG	SIG	-
Gamma rays; e.g., Gamma rays from exploding stars shoot out and are detected. They emit gamma radiation.	6%	14% SIG	SIG	-	SIG	-	SIG	-
Use theory, computers; e.g., They have identified them using Einstein's theories. Through simulations.	9%	27% SIG	SIG	-	SIG	-	SIG	SIG
Supernovae; e.g., They know they exist by watching for stars that go supernova. Because they have recorded/seen when the super novas happen.	1%	6% SIG	-	-	-	-	SIG	-
Use telescopes, satellites; From powerful telescopes. They know because of the SWIFT telescope.	24%	32%	-	-	-	-	-	SIG
Light bending, e.g.; The bending of light toward a black hole. They watch light from stars bend or disappear through space.	11%	4% SIG	-	SIG	-	SIG	-	-
Light, objects fall in; e.g. From inference only. Observing actions of materials moving into the event horizon. Things are pulled into it.	10%	2% SIG	SIG	-	SIG	-	-	-
Effects of gravity; e.g.; Gravitational force. By gravitational pull of the areas around the black hole.	6%	4%	-	-	-	-	-	-

Prior to seeing the film, respondents were most likely to write that scientists know that black holes exist through their use of telescopes or satellites (24%). This relatively non-specific answer remained popular after seeing the film (32%) but the difference in frequencies is not significant.

The film emphasized the work of Andrea Ghez measuring the acceleration of stars around a possible black hole. After seeing the film, audience members were significantly more likely to write that scientists know that black holes exist through their effect on motions of stars (29%). Significantly fewer (4%) participants suggested this possibility prior to viewing the show.

230

The roles played by Einstein's theory and computer simulations in knowing that black holes exist was identified by significantly more respondents after seeing the film (27%) than prior to seeing the film (9%).

That gamma rays are indicative of the existence of black holes was noted by 14% of those who had seen the film, significantly more than by those who had not yet seen the show (6%).

Small portions of those waiting in line to see the film provided answers that reflect misconceptions such as scientists know black holes exist because they see light bending around a black hole (11%) or see light and/or objects falling into a black hole (10%). After viewing the film, frequencies of responses in both of these categories decreased significantly (4%, 2%; respectively).

Sub-samples. After the planetarium experience, females were significantly more likely to say that scientists know that black holes exist because of the motions of surrounding stars, the detection of gamma rays, and the use of theory and computers. They were significantly less likely to think that scientists see light or objects falling into black holes. After seeing the show, males were significantly more likely to write that scientists know that black holes exist because of the motions of surrounding stars and less likely to write about light bending as an indicator of a black hole. Minorities who saw the show were significantly more likely than non-viewers to note that scientists use telescopes or satellites to detect black holes and use Einstein's theories and computer simulations.

To explore quantitative differences in understanding of the previewing sample and the post-viewing sample, responses were given points based on their level of correctness: effect on environment (4 points); spectra/gamma rays (3 pts); theory/computers (2 pts); telescopes/satellites (2 pts); supernovae (2 pts); light bending (1 pt); light/objects falling in (1 pt); gravity (1 pt). The mean achievement score after seeing the film is 2.9 for the whole sample, significantly higher than the mean score of 1.2 prior to seeing the film.[4] All sub-samples scored significantly higher on post-viewing responses than on pre-viewing responses. Viewing the planetarium show significantly increased everyone's understanding of how scientists know black holes exist.

---

[4] Two sample t - test, $p < .0001$.

True-False Test. In the True-False-Don't Know test, "Don't Know" was provided as a possible answer but was scored as "incorrect." Figure 1 compares the distribution of test scores for the previewing and postviewing samples, showing a positively skewed distribution for the posttest scores.

Figure 1. Distribution of Test Scores for Pre- and Post-viewing Samples
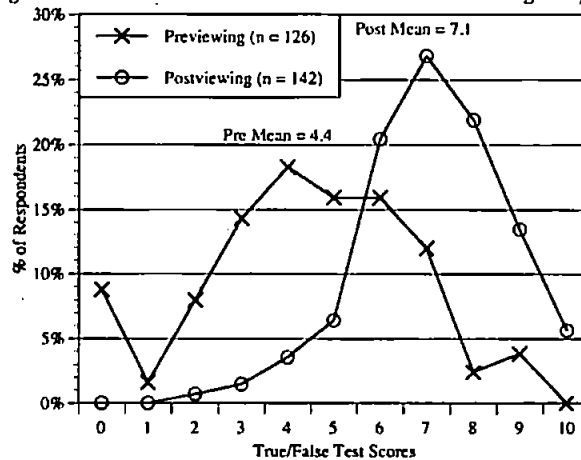
The mean achievement score for the postviewing group is 7.1, significantly higher than the mean score of 4.4 for the previewing group. All postviewing sub-samples scored significantly higher than their equivalent previewing sub-samples (see Table 6 of sub-sample means below):

Table 6. Mean T/F scores for sub-samples

	Pre	Post		Pre	Post		Pre	Post
Adult	4.3	7.2	Male	5.2	7.5	White	4.5	7.3
Teen	4.6	6.7	Female	3.6	6.8	Minority	4.1	6.7

Males scored significantly higher than females on the pretest (5.2 vs. 3.6) and the posttest (7.5 vs. 6.8), but no other pre or posttest differences occurred for gender, age, education, ethnicity and frequency of viewing planetarium films.

Figure 2 provides a more detailed presentation for individual test items. Significantly more film viewers chose correct responses compared to non-viewers for every statement but one ("black holes are passageways to other universes").[5] Seven of the 10 statements were answered correctly by 75% or more of the postviewing audience.

Figure 2: Percent correct responses for each true-false statement before and after viewing film
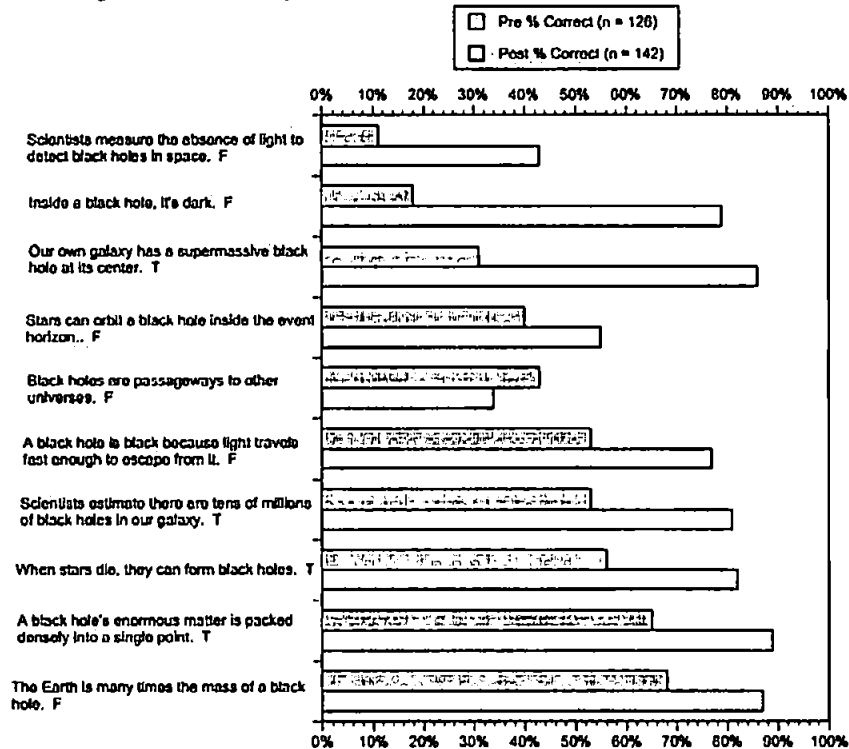
Legend:
- Pre % Correct (n = 126)
- Post % Correct (n = 142)

Statements (top to bottom):
- Scientists measure the absence of light to detect black holes in space. F
- Inside a black hole, it's dark. F
- Our own galaxy has a supermassive black hole at its center. T
- Stars can orbit a black hole inside the event horizon. F
- Black holes are passageways to other universes. F
- A black hole is black because light travels fast enough to escape from it. F
- Scientists estimate there are tens of millions of black holes in our galaxy. T
- When stars die, they can form black holes. T
- A black hole's enormous matter is packed densely into a single point. T
- The Earth is many times the mass of a black hole. F

233

RESULTS: SUBSEQUENT ACTIVITY

Of 121 adult participants who volunteered their email addresses for further contact, 31 (26%) responded within two weeks of being contacted. Of this sub-sample, almost three-quarters recommended the film to others and one-quarter noted taking other actions related to the film – most frequently including the topic in conversations. Few had visited a website related to black holes or had read, seen or heard something in other media that relates to the topic.

❖ 71% of respondents recommended the film to others:

I always recommend people go to the planetarium. I am a huge fan…my dad founded Custom Microwave, and the company works with NASA, Ball, JPL, so it's been a part of my life.

I did recommend it to several people from my work, and friends. I told them how fascinating it was to take some different theories that scientists have developed, and what we know about the earth and black holes.

I enjoyed the show very much and recommended it to my friends. They are majoring in physics at the local university and thought they might find it interesting.

I have spoken to several people about seeing the Black Hole show and recommended to one adult with 3 children as worthwhile to see.

I recommended it to a friend who was reading a bio on Einstein. I said he'd like the movie because it put it into good visual perspective.

I recommended it to my adult children. I told them that it was beautifully done; of great interest; vast subject.

I recommended it to my co-workers. It was a good "movie" to see, it is something different for the kids to see other than the usual Disney movies

I was with my 30 year old son when I saw the show. We talked briefly about it. We both like it, but we both felt we were left with a feeling that we still had questions. .

Recommended it to friends, mentioned that the screen was big and the film was educational

Recommended to colleagues, said it was a good way to get broad perspective on BHs, and that my children liked it

Said that it was an interesting viewpoint and well put together, the images were amazing.

To friends. I told them it would enhance their knowledge and interest in black holes

We talked to 2 people about it and said it was very colorful. We enjoy the '60 minute in space' lectures. By contrast, the BH film contains much less information than do the lectures, so we did not recommend it based on that criterion.

I mentioned to several friends that I had seen a cool show at the IMAX on black holes. I discussed the show with the friend I viewed it with. Wonderful visual effects, but show left me still hungry for more information, more depth, more details.

Yes and we thought it was very good and informative!

I told the people in my immediate office that it was good and they should go see it.

I said it was very informative on Black Holes.

I said it was very interesting.

I was in Denver for a friend's wedding, gave my extra ticket for an IMAX to him. We recommended seeing BH to him and his wife.

My colleagues at work.

I did recommend the movie to a friend

I recommended it to my sister, her husband, and our neighbor.

❖ Since seeing the show, 3% had visited a website related to black holes – respondent printed the film viewing schedule for friends to see the film.

❖ Since seeing the show, 10% had read, seen or heard something in OTHER MEDIA that relates to black holes. Two respondents were reading Brian Greene's "The Elegant Universe," and one respondent watched a related show on the Science channel.

❖ Since seeing the show, 26% noted other actions that relate to seeing the "Black Holes" film:

Had a conversation with my boyfriend, who knows a lot more than me about science, about the film; black holes and the implications of other space phenomenon. The topic has come up several times since.

I sounded very smart at a party recently when I explained that there was a super giant black hole at the center of the galaxy. Then we got into the idea of wormholes and Space Odyssey...

I talked to my brother about it, who is a rocket scientist.

I've thought about the film and astronomy more in general. I've also noticed I refer to the black holes in my conversation, as metaphors or similes. Just last night I was explaining how Argentine tango sucked me in as if it were a black hole.

I have decided I will try to see the one advertised about the Search for other Life.

Just added interest the next time I see an article that would relate.

We actually are planning on taking time at the library because those we went with seem to be enthralled to discover even more.

I homeschool my kindergartener and we are doing a unit about space and black holes, so we have books and movies on the subject. My son is especially interested in black holes, so we are currently looking for pictures or simulated pictures of them to make

MONSTER OF THE MILKY WAY

Summative Evaluation of
Monster of the Milky Way

Executive Summary

Prepared for

Thomas Lucas Productions

By

Valerie Knight-Williams, Ed.D.
Divan Williams Jr., J.D.

With assistance from:
Alice Bernard
Chistina Foltz
David Tower
Ora Srnboyants
Taylor Scigliano

Knight-Williams Research Communications

September 2007

Introduction

Monster of the Milky Way is a one-hour NOVA program designed to stimulate interest and inform the public about the history, science, and future of black holes as a cosmic force. Produced by Thomas Lucas Productions, the program targets general prime time and PBS adult viewers as well as secondary school audiences. The project also includes a number of ancillary educational resources, including a website and educational materials designed to extend and deepen the NOVA viewing experience.

Approximately six months after the broadcast premiere of *Monster of the Milky Way*, Knight-Williams Research Communications, an independent evaluation firm, conducted a summative evaluation to assess the extent to which the NOVA television program and project website accomplished the informal science education goals described in the proposal to The National Science Foundation (NSF). The evaluation examined the extent to which the *Monster of the Milky Way* television program[1]:

- Provided adults and high school youth (ages 15-18) with an overall appealing, engaging, clear and comprehensible viewing experience.
- Increased their understanding of what black holes are, how black holes form, how black holes may affect the matter surrounding them, and the role of black holes in the universe.
- Increased their appreciation of the nature of the event horizon that surrounds black holes—that nothing within the horizon, including light, can escape its gravity.
- Increased their awareness that one of the most destructive objects in the universe—a super massive black hole—exists at the center of our own galaxy.
- Increased their awareness of the current methods astronomers use to research black holes.
- Increased their interest in and curiosity about black holes and led them to think about black holes in a new way.
- Subsequently motivated them to think about or further explore topics featured in the program.

The evaluation assessed impact by randomly assigning a planned sample of adult and youth participants to either a control (non-viewing) group that only completed project questionnaires or a viewing group that watched the program and completed questionnaires. The evaluation then compared the results of assessments completed by both the viewing and control groups at the beginning and end of the evaluation period.

The evaluation also explored the added value of the website, as an ancillary educational resource designed to deepen and supplement viewers' learning from the television program, focusing on the overall appeal, usability, and learning value of the site.

---

[1] Goals are adapted from those stated about the NOVA program on the project website
http://www.pbs.org/wgbh/nova/blackhole/.

Knight-Williams Research Communications

Method

Evaluation design and recruiting

Knight-Williams recruited a planned sample of high school youth as well as adult PBS and general primetime viewers from diverse rural, urban, and suburban areas of the country, with the additional goal of including equal gender representation and approximately 30% minorities. Recruiting occurred through the assistance of evaluation associates with direct access to potential viewers with the appropriate target audience demographics and viewing habits. All adult participants were screened for a minimal level of familiarity and interest in PBS and science/nature programming while youth were screened for enrollment in grades 10-12. Professional scientists, science teachers, and those with previous exposure to *Monster of the Milky Way* were not eligible to participate.

Procedure

As noted in the introduction, the evaluation used an experimental pretest/posttest control group design to assess educational impact. Evaluators randomly assigned participants to two groups (viewing vs. control) stratified by gender and age to achieve a balanced distribution. Although a total of 210 participants were originally recruited for the evaluation, a total of 180 participants completed both pretest and posttest questionnaires within the timeframe allotted for the evaluation, reflecting a response rate of 86%. This total included 101 participants in the viewing group and 79 participants in the control group. Reasons offered for non-completion involved inability to meet the project deadline due to unexpected travel, sickness, or work/school conflicts.

The evaluation procedure worked as follows:

> *Viewing group.* A total of 101 participants viewed *Monster of the Milky Way* at home during a timeframe that generally reflected the original broadcast time (weekday evening). One week prior to viewing the program, participants in this group completed a pre-viewing questionnaire. This group also completed a post-viewing questionnaire immediately after viewing the program.
>
> After completing the post-viewing questionnaire, participants were then asked to freely explore the project website over the course of a two-week period. Viewers were then contacted to complete a follow-up survey that explored the extended influences of the TV program and their experiences at the website. A total of 96 viewers completed this supplemental evaluation in time for inclusion in the report.
>
> *Non-exposure control group.* A total of 79 participants served in a "non-exposure" control group which neither watched the NOVA program nor visited the project website. Participants in this group were only asked to complete questionnaires at the beginning and end of the evaluation period in accordance with the *Viewing group* schedule.

The evaluation then compared the results of the Viewing and Control groups as outlined under Analyses. To ease the burden of the evaluator's requests, participants were provided with honorariums for successfully completing all of the evaluation activities on schedule.

Knight-Williams Research Communications

239

<u>Questionnaires</u>
The project questionnaires ("pretest," "posttest," and follow-up survey for viewers) were administered online and contained multiple question sets.

The pretest asked all evaluation participants about their:
- Demographic and other background information including: gender, age, race/ethnicity, educational background, occupational status, television viewing habits, and interest in and knowledge of astronomy and black holes.
- Knowledge of the content addressed in *Monster of the Milky Way* relating to black holes (as specified on page 1) in the form of true/false, multiple choice, and open-ended questions. Assessment items were developed in collaboration with the project director and after reviewing the program script to ensure consistency in language. Assessment items were pilot tested with 10 adults and youth fitting the target audience profile for readability, comprehension, and ease of completion. Items were randomly presented throughout the assessment rather than presented according to content area.

On the posttest, participants in the control and viewing groups were again asked about the questions listed under the preceding bullet point. Viewers were additionally asked about the following issues relating to the program:
- With whom they watched the *Monster of the Milky Way* program and whether and how their viewing was disrupted.
- The extent to which they: liked or disliked the programming; perceived the content as boring or interesting; found the presentation visually dull or exciting; found the storytelling boring or engaging, found the presentation clear or confusing; and felt the programming had too much or too little information, too much or too little science, and too much or too little explanation of scientific principles.
- What they liked and disliked about the program.
- How much they felt they learned from *Monster of the Milky Way* and what they felt were the most interesting things they learned.
- Whether and how they felt the program caused them to think about black holes in a new or different way.
- Whether they expected they would recommend the program to others.
- How successful they felt the programming was in communicating: what black holes are; how black holes form; that black holes shape the universe around them in important ways; the different methods astronomers can use to research black holes; how scientists are proving that a super massive black hole exists at the center of our galaxy; that our black hole is a ticking time bomb - it's calm now but explosive down the line; and the different career opportunities that exist in astronomy and science.
- Whether the program increased or decreased their interest in black holes, the methods scientists use to study black holes, science in general, and science related careers (youth only).
- Whether they felt they learned anything new about scientists from watching *Monster of the Milky Way* and perceived that the scientists were good role models for youth (youth only).

The follow-up viewer questionnaire focused on:
- The longer-term appeal and perceived value of the NOVA program.
- The nature and scope of viewers' thoughts and conversations about black holes with family,

Knight-Williams Research Communications

friends, and co-workers.
- What viewers did at the website, what they liked and disliked about the website, what they learned, and whether their experiences motivated them to take additional actions to learn more about topics featured in the program.

Analyses

Statistical analyses were conducted on all quantitative data generated from the evaluation to examine the impact of the program and relationships with the demographic and background variables measured. Demographic and background variables included: gender (female vs. male), age (youth 15-18 vs. adults 19 and above), frequency of watching PBS (daily or weekly vs. monthly or less than monthly), frequency of watching science/nature shows (daily or weekly vs. monthly or less than monthly), overall interest in astronomy (little or no interest vs. moderate or a lot of interest) and knowledge of astronomy (little or no knowledge vs. moderate or a lot of knowledge). Given the relatively small number of participants in the racial/ethnic groups represented, results related to this demographic factor were not explored.

To explore for possible significant differences between and within groups the analyses used Chi-square and t-tests as appropriate. [2] Statistically significant findings (hereafter referred to as "significant") at $p \le .05$ are reported in the text. To help determined whether a significant difference was a difference of practical concern, effect sizes were also computed using Cohen's d measure.[3]. As noted by Tahlheimer and Cook (2002) *"whereas statistical tests of significance tell us the likelihood that experimental results differ from chance expectations, effect-size measurements tell us the relative magnitude of the experiment treatment. They tell us the size of the experimental effect."* [4] Effect sizes for the significant differences between groups are reported in the text where appropriate. Following Cohen's interpretation (Cohen, 1992),[5] .2 is indicative of a small effect, .5 a medium effect, and .8 a large effect.

Content analyses were performed on the qualitative data generated in the open-ended questions on the pretests, posttests, and follow-up viewer questionnaire. All analyses were conducted by two independent coders. Any differences that emerged in coding were resolved with the assistance of a third coder.

---

[2] When examining subgroups with two categories, Levene's test was used to determine whether 2-sample t-tests or Pooled t-tests were appropriate for testing the means of the measured variables.

[3] d is defined as the difference between the 2 means divided by the pooled standard deviation for those means.

[4] Thalheimer, W. and Cook, S. (2002). How to calculate effect sizes from published research: A simplified methodology. *Work-Learning Research*, p. 2.

[5] Cohen, J. (1992). A Power Primer. *Psychological Bulletin*, 112 (1), 155-159.

Sample demographic and background information

A total of 101 viewing and 79 control group participants completed questionnaires that subsequently formed the basis for this evaluation report.[6] Chi-square analyses showed that the viewing and control groups did not differ significantly with respect to the demographic or background variables measured in the evaluation, including: gender, age group, race, ethnicity, occupation, education, frequency of viewing PBS, frequency of viewing NOVA, frequency of viewing science/nature shows, or perceived interest in and knowledge of astronomy.

The viewer portion of the sample included:

- About the same percentage of females (49%) and males (51%).
- A wide range of ages, spanning 15-67 years, with an overall mean age of 29.
- About the same percentage of adults (53%) ages 18 and older and youth participants (47%) ages 18 and under.
- A racial distribution comprising 72% Whites and 28% minorities, including: 5% African-American/Black, 5% Asian, 2% Native Hawaiian or Pacific Islander, 1% Native American Indian/Alaskan Native, and 17% mixed-race viewers; One-sixth (15%) of the group reported that they were of Hispanic origin.
- A comparable percentage of employed individuals (42%) and students (47%).
- A combination of regular and sometime viewers of PBS programs, with 40% reporting they watched PBS either daily or weekly, 19% reporting they watched monthly, and 42% reporting they watch less than monthly.
- A combination of regular and sometime viewers of science/nature programs, with 36% reporting they watched such programs either daily or weekly, 35% reporting they watched monthly, and 30% reporting they watched monthly or less than monthly.
- A combination of regular and sometime viewers of NOVA, with 42% reporting they watched such programs either regularly or occasionally, 35% reporting they watched seldom, and 22% reporting they never watched NOVA.
- A combination of individuals interested in astronomy, with more than half (53%) saying they were moderately or very interested in this subject, 21% reporting some interest, and 27% reporting little or no interest.
- A combination of individuals reporting they knew a little or nothing about astronomy (62%), while 24% reported some knowledge of the subject, and 15% reported they had a moderate amount or a lot of knowledge about the subject.
- A very high percentage of individuals (97%) who said they had heard of black holes before, yet a somewhat smaller percentage of individuals who believed that black holes are real (75%) versus only in science fiction (25%).
- A combination of individuals who said they knew little or nothing about black holes (66%), with 22% reporting they had some knowledge about black holes, and 12% reporting a moderate amount or a lot of knowledge.

---

[6] Although a total of 210 participants were initially recruited for the evaluation, 30 participants did not complete the evaluation requirements on schedule and were excluded from the analysis. Reasons reported for lack of completion included sickness, unexpected travel, or work/school conflicts that precluded participants from completing the evaluation requirements on time.

Knight-Williams Research Communications

Findings

Part 1: The Viewing Context:
With whom viewers watched *Monster of the Milky Way* and whether their viewing was disrupted

The evaluation generally found that the majority of viewers watched the program alone, and without disruption. Most also said that they didn't watch the program when it aired in October because they didn't know about it. More specifically:

◘ **The majority of viewers (67%) watched the NOVA program alone.** Just over one-sixth (17%) said they watched the program with a friend while smaller percentages reported watching with a spouse/partner (8%), child (5%), or some combination of spouse/partner, friends, or children (3%).

◘ **While nearly three-quarters (72%) said they watched the program without disruption,** the remaining viewers experienced some disruption that briefly interrupted their viewing experience. The most frequently mentioned disruptions were: answered phone or door (9%) or briefly fell asleep/zoned out (6%). Other disruptions mentioned by individual viewers (13%) included one of the following: made snack, tended to family member, was distracted by dog barking, or had to fix DVD pausing on graphics.

◘ When asked why they didn't watch the *Monster of the Milky Way* program when it aired on PBS during October, more than four-fifths (86%) of the group said they didn't know about the program. Just a few viewers (5%) said they knew about it but were unable to watch at the time it aired, and one viewer (1%) said the subject matter didn't appeal.

Part 2: Viewers' assessment of the overall appeal and entertainment value of *Monster of the Milky Way*

The program was very well received by the adult and youth audience of viewers randomly assigned to watch the *Monster of the Milky Way*. These viewers generally liked the program, found the content and storytelling interesting, and agreed that the program was visually exciting. They were also consistently able to articulate various things they liked about the program and felt they were likely to recommend the program to others. More specifically:

◘ **Viewers generally reported they liked the program.** When asked to rate how they much they liked or disliked the program using a scale of 1 (disliked overall) to 7 (liked overall) the mean rating for the viewing group as a whole was 5.8. Adults rated their liking of the program significantly higher than did youth and more frequent viewers of PBS rated their liking of the program significantly higher than did less frequent viewers.

7

243

➲ When asked to discuss what they most liked about the program, four major themes emerged across viewers' responses, with the largest group of viewers (39%) applauding the program's use of visuals, and in particular the use of graphics, animation, and photography. Viewers described these visual elements as *dramatic, outstanding, amazing,* and/or *beautiful,* with many further noting that they helped them understand the subject matter of black holes. One-third (33%) of the viewers, meanwhile, said they liked learning new information about black holes, especially relating to what they are, how they form, how they work, and/or how scientists study them. One-fifth (21%) praised some aspect of the program's story-telling approach, and in particular its use of drama, mystery, analogies, humor, and/or its clear and easy-to-follow explanations. Finally, a somewhat smaller percentage of viewers (17%) said they enjoyed the scientists featured in the program, describing them as *knowledgeable, enthusiastic, engaging, personable* and/or as *effective communicators.*

➲ When asked to describe what, if anything, they disliked about *Monster of the Milky Way* no one issue stood out as a major problem for the majority of the group. The most common complaint was mentioned by one-quarter (25%) of the viewers and involved their desire for additional explanation or information where scientific concepts seemed hard to understand, confusing, or less frequently, contradictory or over-reaching. Other dislikes were mentioned by less than one-sixth of the viewers and focused on something relating to the: featured scientists (13%), visuals (8%), viewers' perception that the narration or scientists sometimes repeated or over-explained information (8%), the characterization of black holes as "monsters" (3%) or viewers' uneasiness about the dangers that black holes pose (3%). Other individual viewers each expressed the view that the program was too short or that the editing was somewhat choppy, edgy, or MTV like. Nearly one-third (30%) of the viewers indicated there wasn't anything they disliked, with many instead adding general praise for the program.

➲ Viewers generally agreed that *Monster of the Milky Way* provided interesting content. When asked to rate how interesting they found the content using a scale of 1 (boring) to 7 (interesting), the mean rating for the viewing group as a whole was 5.9. There were a few subgroup differences for this item, however. First, adults rated their interest in the program content significantly higher than did youth. Second, viewers who rated themselves as more knowledgeable about astronomy rated their interest significantly higher than did those who rated themselves as less knowledgeable. And finally, more frequent viewers of PBS rated their interest in the program content significantly higher than did less frequent viewers. Among the viewers who commented on the appeal of the content, most enthusiastically commented that they found the subject matter on the order of *fascinating* or *mesmerizing.*

➲ Viewers generally agreed that the program presented engaging storytelling. When asked to rate the program's storytelling on a scale of 1 (boring) to 7 (engaging), the mean rating for the viewing group as a whole was 5.4. A couple of subgroup differences were found for this item in that adults rated the storytelling significantly higher than did youth and more frequent viewers of PBS rated the storytelling significantly higher than did less frequent viewers. Among the many adults and youth who chose to comment on the program's storytelling approach, the majority offered positive remarks. Some characterized the presentation as interesting or entertaining, while others appreciated that the scientific information was accessible or that the scientists were engaging. Meanwhile, a few adults and youth took issue with some aspect of the program's storytelling. The adults in this case described the metaphors

8

as overused, the editing as *choppy* in places, or the music as *cheesy* or too geared to a younger crowd. Youth meanwhile described the presentation as occasionally dull, repetitive, too long, or featuring scientists with dull voices.

⊃ **Viewers generally agreed that the program was visually exciting.** When asked to rate the program's visual excitement on a scale of 1(visually dull) to 7 (visually exciting), the mean rating for the viewing group as a whole was 6.0. As with the rating for storytelling, adults rated the program's visual excitement significantly higher than did youth and frequent viewers of PBS rated the visuals significantly higher than did less frequent viewers. Moreover, viewers who rated themselves as more knowledgeable about astronomy rated the visuals significantly higher than did those who rated themselves as less knowledgeable. In their explanations of their ratings, several adults and youths praised the program's visual qualities, most often noting that they were *appealing, beautiful, eye-catching* or helped them to understand the subject matter presented. Just a few viewers, all adults, pointed to something about the program's visuals that they disliked, most often focusing on graphics or clips being overused, confusing, or relatively unappealing compared to those featured in previous programming viewed.

⊃ **Viewers agreed that the program was worthy of recommendation.** When asked to rate their likelihood of recommending the program using a scale of 1 (would not recommend) to 7 (would recommend), the mean rating for the viewing group as a whole was 5.9. There was one subgroup difference found for this item wherein adults indicated they were significantly more likely to recommend the program than did youth.

Part 3. Viewers' assessment of *Monster of the Milky Way's* clarity, density of information, science, and science explanations, and success in presenting seven themes about black holes

Viewers generally concurred that the program was clear, and struck the right balance in terms of the amount of information, science, and scientific explanations provided. Viewers also generally felt that the program was successful in communicating the seven informal science education themes asked about in the evaluation. More specifically:

⊃ **Viewers generally agreed that the program offered a pretty clear presentation.** When asked to rate how clear or confusing they found the program using a scale of 1 (confusing) to 7 (clear), the mean rating for the viewing group as a whole was 5.6. Four subgroup differences were found for this item as follows. First, adults rated the program's clarity significantly higher than did youth. Second, more regular viewers of science/nature programs rated the program's clarity significantly higher than did less frequent viewers. Third, viewers who rated themselves as more knowledgeable about astronomy rated the clarity significantly higher than did those who rated themselves as less knowledgeable. And finally, more frequent viewers of PBS rated the clarity significantly higher than did less frequent PBS viewers.

⊃ **Viewers also generally felt that the amount of information presented in the program was about right.** When asked to rate the amount of information on a scale of 1 (too little) to 7 (too much), the mean rating for the viewing group as a whole was 4.3. One subgroup difference was found for this item as viewers who rated themselves as less interested in astronomy rated

9   Knight-Williams Research Communications

the amount of information significantly higher than did those who rated themselves as more interested in the subject. Most of the adults and youths who commented on their information density ratings indicated they felt the balance was generally about right for them. Several of their comments focused on the value of the supporting visuals presented. A few viewers meanwhile, all adults, said they would have preferred even more depth to the amount of information presented in the program. Just a few viewers suggested the level or amount of information was too high, noting lack of prior familiarity with black holes or astronomy in general.

Ɔ Viewers generally agreed that the amount of science was about right. When asked to rate the amount of information on a scale of 1 (too little) to 7 (too much), the mean rating for the viewing group as a whole was 4.3. One subgroup difference was found for this item as youth rated the amount of science significantly higher than did adults.

Ɔ Viewers generally further agreed that the program offered just enough explanation of scientific principles. When asked to rate the explanations on a scale of 1 (too little) to 7 (too much), the mean rating for the viewing group as a whole was 4.0. There were no subgroup differences for this item. Most who commented on their rating reiterated that they found the program clear or easy to follow. Some viewers however, particularly youth, felt there were some concepts they would have liked to see explained in greater detail, such as: the use of x-rays, what Einstein thought about black holes, basic concepts in astronomy and physics, and the meaning of terms like 'cosmos.'

Ɔ Viewers rated the program as successful in presenting seven different black hole and astronomy science themes, although some themes received higher mean ratings than others. Using a scale of 1 (not at all successful) to 7 (extremely successful):

• Viewers generally rated the program as very successful in presenting what black holes are (mean rating, 6.0). Two subgroup differences were found for this item. First, adults rated the program's success in presenting what black holes are significantly higher than did youth. Second, viewers who rated themselves as more interested in astronomy rated the program's success in presenting this topic significantly higher than did those who rated themselves as less interested in this subject.

• Viewers generally rated the program as moderately to very successful in presenting how black holes form (mean rating, 5.8). One subgroup difference was found in this case, as adults rated the program's success in presenting this topic significantly higher than did youth.

• Viewers also rated the program as moderately to very successful in presenting that black holes shape the universe around them in important ways (mean rating, 5.8). Here again, adults rated the program's success in presenting this topic significantly higher than did youth.

• Viewers also rated the program as moderately to very successful in proving that a super massive black hole exists at the center of our galaxy (mean rating, 5.6). Once

again, adults rated the program's success in presenting this topic significantly higher than did youth. None of the viewers chose to explain their rating of this theme.

- Viewers again rated the program as moderately to very successful in presenting the different methods astronomers can use to research black holes (mean rating, 5.5). Adults again rated the program's success in presenting this topic significantly higher than did youth. Also, viewers who rated themselves as more knowledgeable about astronomy rated the program's success in presenting this topic significantly higher than did those who rated themselves as less knowledgeable.

- Viewers generally felt the program was moderately successful in showing that our black hole is a ticking time bomb – it's calm now but explosive down the line (mean rating, 5.0). Here again, adults rated the program's success in presenting this topic significantly higher than did youth.

- Finally, viewers felt the program was somewhat successful in presenting the different career opportunities that exist in astronomy and science (mean rating, 3.9). In contrast to the age-group findings reported for the previous themes, however, in this case, youth rated the program's success significantly higher than did adults. Among the several adults to comment on their ratings, most noted that they didn't recall this focus in the program, although a few acknowledged that the program did demonstrate or showcase scientists' talents and methods of work, or noted the program's inclusion of female scientists.

Part 4. Viewers' learning from *Monster of the Milky Way*

To understand the learning value of *Monster of the Milky Way*, viewers were asked to: rate how much they felt they learned from the program, rate it's effect on their level of curiosity, describe the most interesting things they learned from the program, describe whether and how the program caused them to think about black holes in a new or different way, and describe what they learned about scientists from the program. Additionally, to estimate viewers' understanding of black holes and other science content presented in the program, participants in both the viewing and control groups were each asked to complete a combination of true-false and multiple choice items about specific themes presented in the program (described in the report). The results from the above set of assessments are summarized below.

- ➲ Viewers felt the program had high learning value for them personally. When asked to rate how much they felt they learned from *Monster of the Milky Way* on a scale of 1 (learned nothing) to 7 (learned a lot) the mean rating for the viewing group was 6.0. No subgroup differences were found for this item. Several youth and a few adults commented on their ratings of the program's learning value, generally noting that the program: answered questions they had about astronomy, taught them about topics with which they were previously unfamiliar, increased their interest in black holes, and/or led them to think further about research on black holes.

⊃ Viewers also felt the program generally increased their curiosity. Again using a scale of 1 (decreased curiosity) to 7 (increased curiosity), the mean rating for the viewing group was 5.7. One subgroup difference was found for this item as adults felt the program's effect on their curiosity was significantly higher than did youth.

⊃ Viewers generally felt that the program increased rather than decreased their interest in learning more about: black holes, scientific methods to study black holes, and science in general. Using scales of 1 (decreased strongly) to 7 (increased strongly) the topic of "black holes" received the highest mean rating (5.9), followed by the "methods scientists use to study black holes" and "science in general" (both at 5.4). Several subgroup differences were found as follows:

   ✓ Interest in black holes: Adults rated their interest in learning about black holes significantly higher than did youth.

   ✓ Interest in methods: Adults rated their interest in learning about the methods scientists use to study black holes significantly higher than did youth. Viewers who rated themselves as more interested in astronomy rated their interest in learning about this topic significantly higher than did those who rated themselves as less interested in astronomy.

   ✓ Interest in science: Adults rated their interest in learning about science significantly higher than did youth. Also, more frequent viewers of science/nature programs rated their interest in learning about science significantly higher than did less frequent viewers. Similarly, more frequent viewers of PBS rated their interest in learning more science significantly higher than did less frequent viewers. Finally, viewers who rated themselves as more interested in astronomy rated their interest in learning about science higher than did those who rated themselves as less interested in astronomy.

⊃ Youth viewers who were additionally asked to rate their interest in science careers as a result of watching the program tended to agree that the program somewhat increased their interest in this regard (mean rating, 4.8). Youth who rated themselves as more interested in astronomy rated their interest in learning about science careers higher than did those who rated themselves as less interested in astronomy.

⊃ When asked to describe the most interesting things they learned from watching *Monster of the Milky Way*, all of the viewers discussed at least one thing that interested them and many mentioned two or more things. The majority of their responses focused on information they learned about: black hole "behavior" or how black holes work, the impact of black holes on the universe around them, the methods scientists use to study black holes, and/or information about the size, prevalence, and/or formation of black holes. The largest percentage of viewers, however, nearly two-fifths (38%) of the group, said they were interested in information presented in the program about how black holes work, most often pointing to facts or concepts they learned about gravitational pull, how black holes emit energy, the fact that nothing can escape them, and/or that they play an organizing role in universe. Nearly one-third (30%) of the viewers, meanwhile, were interested in information presented on black hole research, focusing on the methods scientists use to study them.

12   *Knight-Williams Research Communications*

Meanwhile, more than one-quarter (27%) of the viewers discussed learning the fact that back holes exist in every galaxy, with many of these viewers further noting that black holes are found in the center of larger galaxies. Finally, smaller percentages of viewers, less than one-tenth of the group in each case, said they were interested in information they learned about how big black holes are (9%), how black holes are formed (9%), that there are many black holes (6%), and/or the prediction that the Milky Way and Andromeda galaxies will eventually collide (6%).

➲ **Seeing the program significantly affected viewers' self-assessed understanding of black holes.** Participants in both the viewing and control groups were asked to rate their level of understanding of "black holes" at pretest and again at posttest using a scale of 1 (don't understand at all) to 7 (could explain to others). At pretest both viewing and control group participants generally indicated they had little understanding of black holes (3.1 vs. 2.9 respectively). The two groups' mean scores were not significantly different. At posttest, however, the mean rating for the viewing group increased to 5.0, which was significantly higher than the group's pretest mean rating of 3.1. More importantly, the viewing group's mean posttest rating was significantly higher than the control group's posttest mean rating of 3.0, with the effect size being 1.38, considered a large effect.

There were two subgroup differences found for this question relating to interest in and knowledge of astronomy. Viewers who rated themselves as more knowledgeable about astronomy rated their level of understanding of black holes significantly higher than did those who rated themselves as less knowledgeable. Moreover, viewers who rated themselves as more interested in astronomy rated their level of understanding significantly higher than did those who rated themselves as less interested in this subject.

➲ **All but one-tenth of the viewers (88%) felt that the program led them to think about black holes in a new or different way.** When asked to explain the change, five main themes emerged across their responses. Two-thirds (61%) of the viewing group, about an equal number of adults and youth, indicated that as a result of viewing the program they had a much clearer understanding of the fact that black holes are real, exist in outer space, and aren't just part of science fiction. Many of these viewers further elaborated that they learned basic information that dispelled previous myths they previously held about black holes and/or that helped them to more concretely understand what black holes are, how they form, where they are located, and that there are many. Nearly one-quarter (22%) of the viewers, mostly adults, felt they had a greater appreciation of the importance of black holes to the universe. Meanwhile, one-sixth (14%) of the viewers, about an equal number of adults and youth, were of the opinion that the program increased their fear of or concern about black holes, as reflected in their responses characterizing black holes as *scary, monstrous,* or *dangerous.* More than one-tenth (12%) of the viewers, mostly youth, felt the program gave them a heightened sense of the sheer power of black holes, particularly relating to how they pull in matter and emit energy. Several viewers (8%), mostly adults, felt the program decreased their fear or concern about the dangers posed by black holes, most often noting that they learned that they have no control over black holes or that black holes won't affect them or their children. Finally, a handful of viewers (6%), all youth, said they felt the program did not change the way they thought about black holes, either noting a lack of interest in the subject or that they didn't learn much new information.

249

⊃ Seeing the program significantly affected viewers' estimation of the impact black holes have on the universe around them. To estimate the impact of *Monster of the Milky Way* on viewers' estimation of the impact black holes have in shaping the universe around them participants in both the viewing and control groups were asked to rate how much of an impact they thought black holes have in shaping the universe around them on a scale of 1 (no impact) to 7 (great impact). At pretest the viewing and control groups on average both estimated that black holes have a moderate impact (mean ratings 4.7 vs. 4.5 respectively). The two groups' mean scores were not significantly different. At posttest however, the mean rating for the viewing group increased to 6.1, which was significantly higher than the group's pretest mean rating of 4.7. More importantly, the viewing group's mean posttest rating was significantly higher than the control group's posttest mean rating of 4.7, with the effect size being 1.0, generally considered a large effect. There was one subgroup difference for this item as adults rated the impact significantly higher than did youth.

Viewers were also invited to explain their ratings. One-third (35%) of the viewers explained that black holes swallow, suck, pull in, or devour matter, planets, or galaxies. One-fifth provided general non-specific answers that generally noted that black holes have a role in shaping the universe around them without specifying how. One-sixth (15%) observed that black holes affect the size and/or organization of galaxies or the universe. One-tenth (10%) noted that black holes change the trajectory of stars or orbits, while a few viewers each said that black holes: are located at center of galaxies (7%), spew out energy (6%), clean debris (3%), and/or gave another response. Finally, a few viewers (5%) wrote that they didn't know how black holes shape the universe around them.

⊃ Comparing the two groups' overall scores on a 27-point assessment that included a series of true/false and multiple choice questions, the evaluation found that viewing the program significantly improved viewers' knowledge of black holes and black hole research. Out of a possible score of 27 points, the viewing group, on average, scored 9 points at pretest while the control group scored 8 points. The two groups' scores were not significantly different. At posttest however, the viewing group's mean score increased to 20 points, which was significantly higher than the group's pretest mean score of 9. Even more importantly, the viewing group's mean posttest score was significantly higher than the control group's posttest mean score of 9, with the effect size being 1.77, generally considered a large effect.

Three subgroup differences were found within the viewing group's overall assessment scores at posttest. First, adults scored significantly higher on the assessment than did youth (22/27 vs. 16/27). Second, viewers who rated themselves as more knowledgeable about astronomy scored significantly higher than did those who rated themselves as less knowledgeable (22/27 vs. 19/27). And finally, viewers who rated themselves as more interested in astronomy also scored significantly higher than did those who rated themselves as less interested (21/27 vs. 18/27).

Looking at viewers' performance on the four specific content areas of the assessment, the evaluation further found viewers showed significant improvement in each case. The findings for each assessment are provided below, relating to: a) the location and existence of black holes, b) the formation of black holes, c) how black holes work, and d) black holes research and methods of study.

a) Learning related to the location and existence of black holes

To estimate viewers' learning about content presented in the program about the location and existence of black holes, participants in both groups were presented with 4 true/false questions and 1 multiple choice question. The true/false statements included: *Only a few galaxies in the universe have black holes (false); Black holes are typically found in the center of planets like Earth or Mars (false); All the big galaxies in the universe have a black hole at their center (true), and Black holes have not yet been located in our galaxy (false).* The multiple choice question asked participants to indicate where black holes occur, with the correct response being "outer space."

The evaluation found that seeing the program significantly improved viewers' knowledge of the location and existence of black holes as measured by the five questions asked on the assessment. At pretest the viewing group scored an average of 2.2 out of a possible 5 points while the control group scored an average of 2.0 points. The two groups' mean scores were not significantly different. At posttest, however, the viewing group's mean score increased to 4.3, which was significantly higher than the group's pretest mean score of 2.2. Even more importantly, the viewing group's mean posttest score was significantly higher than the control group's posttest mean score of 2.2, with the effect size being 1.62, generally considered a large effect. One subgroup difference was found within the posttest scores of the viewing group in that that adults scored significantly higher on this portion of the assessment than did youth.

b. Learning related to the formation of black holes

To estimate viewers' learning about content presented in the program relating to the formation of black holes, participants in both groups were presented with 3 true/false questions: *Black holes form in the death of large stars (true); Scientists believe that our sun will one day turn into a black hole (false); and Black holes are the remnants of collapsed/dead stars (true).*

Seeing the program significantly improved viewers' knowledge of the formation of black holes, as measured by the three questions asked in the assessment. At pretest the viewing group scored an average of 1.2 points out of a possible 3 points while the control group scored an average of 1.1 points. The two groups' mean scores were not significantly different. At posttest, however, the viewing group's mean score increased to 2.0, which was significantly higher than the group's pretest mean score of 1.2. Even more importantly, the viewing group's mean posttest score was significantly higher than the control group's posttest mean score of 1.3 with the effect size being .78, generally considered a medium effect.

With respect to subgroup differences among the viewers' posttest scores, three were found. Adults scored significantly higher on this portion of the assessment than did youth. Also, viewers who rated themselves as more knowledgeable about astronomy scored significantly higher than did those who rated themselves as less knowledgeable. Finally, viewers who rated themselves more interested in astronomy scored significantly higher than did those who rated themselves less interested.

c. Learning related to how black holes work

To estimate viewers' learning about content presented in the program about how black holes work, participants in both groups were presented with 6 true/false questions and 2 multiple

15   Knight-Williams Research Communications

251

choice questions. The true/false statements included: *When matter falls toward a black hole it gets sucked straight in (false); When something falls into a black hole, it eventually comes back out (false); Black holes have a region surrounding them beyond which nothing can escape, not even light (true); Black holes are like cosmic vacuum cleaners that clean the dust and debris that accumulate in outer space (false); Black holes emit or shoot energy outward (true); and Black holes have periods of high activity and low activity (true).* One of the two multiple choice questions asked participants whether scientists think that the black hole at the center of the Milky Way galaxy is generally active or inactive at present, with the correct response being "active." The second multiple choice question asked viewers to select which of several response options can escape from being pulled into a black hole, with the correct response being "nothing can escape."

Seeing the program significantly improved viewers' knowledge of how black holes work as measured by the eight questions asked on the assessment. At pretest both the viewing and control groups scored an average of 2.3 points out of a possible 8 points. At posttest, however, the viewing group's mean score increased to 5.5, which was significantly higher than the group's pretest mean score of 2.3. Even more importantly, the viewing group's mean score of 5.5 was significantly higher than the control group's posttest mean score of 2.3, with the effect size being 1.7, considered a large effect. There was one subgroup difference found for this item at posttest within the viewing group as adults scored significantly higher on this portion of the assessment than did youth.

d. Learning related to black holes research and study methods

To estimate viewers' knowledge of content presented about black holes research and methods of study, participants in both groups were presented with 1 true/false question and 2 multiple choice questions. The true/false statement was: *Black holes were described by the theories of Albert Einstein (true).* One of the two multiple choice questions asked participants how scientists determine whether there's a black hole in a certain part of a galaxy, with the correct responses being: "Clock the speed of stars moving around its suspected location," "Look for a jet of high energy particles," and "Look for sudden flare ups of radiation." The second question asked participants which of several methods scientists use to study black holes, with the correct responses being: radio receivers, x-ray detectors, telescopes, and computer simulations.

Seeing the program significantly improved viewers' knowledge of black hole research and methods of study as measured by the 3 questions asked on the assessment. At pretest the viewing group scored an average of 1.9 points out of a possible 8 points, while the control group scored an average of 1.8 points. The two groups' mean scores were not significantly different. At posttest, however, the viewing group's mean score increased to 5.5 which was significantly higher than the group's pretest mean score of 1.9. Even more importantly, the viewing group's mean posttest score was significantly higher than the control group's posttest mean score of 2.1, with the effect size being 1.5, generally considered a large effect.

Two subgroup differences were found among the posttest scores within the viewing group. First, adults scored significantly higher on this portion of assessment than did youth. Second, viewers who rated themselves as more interested in astronomy scored significantly higher than did those who rated themselves as less interested.

d. Learning related to miscellaneous attributes of black holes

To estimate participants' learning about miscellaneous attributes of black holes, participants in both groups were presented with 2 true/false questions and 1 multiple choice question. The true/false statements included: *Black holes are invisible* and *Black holes are thought to be the density of water*. The multiple choice question asked viewers whether they thought black holes are real or only in science fiction.

Seeing the program significantly improved viewers' knowledge of miscellaneous attributes of black holes as measured by the 3 questions asked in the assessment. At pretest both the viewing and control groups scored an average of 1.4 points out of a possible 3 points. The two groups' mean scores were not significantly different. At posttest, however, the viewing group's mean score increased to 2.4, which was significantly higher than the group's pretest mean score of 1.4. Even more importantly, the viewing group's mean posttest score was significantly higher than the control group's posttest mean score of 1.3, with the effect size being 1.3, generally considered a large effect. One subgroup difference was found among the posttest scores within the viewing group in that adults scored significantly higher on the assessment than did youth.

⊃ **About three-fifths of the viewers (58%) perceived that they learned something new about scientists from the program, while about two-fifths (39%) felt they hadn't.** Those who felt they learned something new were asked to explain what they learned. No one theme stood out for a majority of the viewers, but four different themes were represented across their comments. One-fifth of the viewers (20%) felt they learned that scientists can be very passionate, dedicated, and/or enthusiastic about their work. More than one-tenth meanwhile (13%) felt the program gave them a greater appreciation for the idea that scientists are actually normal people and have a sense of humor, are personable, imaginative, and not always arrogant. Several viewers (11%) felt they learned about scientists' research methods. And finally, a few more viewers (5%) felt they acquired a greater awareness that scientists are from diverse backgrounds.

⊃ **Most (80%) youth viewers agreed that the scientists featured in the program were good role models for people their age, with the main reasons being: that they show passion or dedication for their work (39%), that they are intelligent (20%), or that they come across as normal people (9%).** A small group of youth (20%) meanwhile felt that the scientists were not good role models for people their age. The most common reason, mentioned by one-tenth (10%) of the youth, was that they seem generally out of touch with youth or have a different perspective. A few youth (7%) explained that youth don't have much interest in astronomy. Finally, a couple of youth (4%) felt the scientists were too old.

⊃ **When viewers were asked if there was anything else they wanted to share about their experience viewing** *Monster of the Milky Way*, more than two-fifths (45%), slightly more adults than youth, praised the program's overall appeal and informative value. Several viewers (11%), all adults said they showed the program to someone else or would recommend it. Several more viewers (11%), about an equal number of adults and youth, offered comments

17

relating to NOVA more generally. Several viewers (9%) mostly adults said they would like to see more programming on astronomy or black. A few more viewers, mostly adults, appreciated that the program was put together in a way that was easy for them to understand/follow (3%) or felt the program left them with unresolved or new questions. A couple of adult viewers (2%) observed that they felt the title of the program was misleading or threw them off. Finally, one youth praised the program for its interesting topics and suggested the use of more youth in the program to appeal to a younger audience.

Part 5: The extended Influences of *Monsters of the Milky Way*

All viewing participants were asked to complete a follow-up online survey within two weeks of viewing the program that asked them to reflect on any thoughts or conversations they may have had about material presented in *Monster of the Milky Way* since viewing. The evaluation found that more than two-thirds (66%) of the viewers reported that they had continued to think about *Monster of the Milky Way* in the weeks since they viewed the program. More than half (53%) said that they had discussed the program with friends, family, or co-workers. Nearly one-fifth (18%) said they had seen something on TV that had reminded them of the program. Several viewers said that they had read something in a magazine, book, or online (7%) or heard something on the radio (7%) that reminded them of the program.

More specifically:

�); More than two-thirds (66%) of the group reported that they had discussed the program with their significant others, family, friends, roommates, and/or co-workers. Most often these viewers said they discussed information they learned about black holes or they generally praised and/or recommended the program to a spouse, parent(s), or friend(s)

�); Nearly one-fifth (18%) reported that they had seen something on television or in a movie that made them think about something in the program. Eight viewers, a combination of adults and youth, explained that they had watched televisions programs as diverse as Star Wars, Star-Trek, History Channel programming on either the Bermuda Triangle or black holes, or other NOVA or Discovery channels programs. A few viewers, mostly adults, said they watched a movie such as Zathura, or they saw a movie in science class, from Netflix, or in some other context. A few others adults and youth said they were reminded of the program when viewing a television advertisement for one of the following: NOVA, a new movie called Sunshine, or even a beer commercial.

�); Several (7%) viewers said they had read something in a newspaper, magazine, book, or other publication that made them think of the program. These viewers talked about reading information in a book or website about topics as diverse as dust, global warming, and/or an artist interested in over-looked objects or scenes.

�); Several (7%) viewers, mostly adults, indicated they had heard something on the radio that made them think of the program. These viewers talked about listening to Deep Purple, Pink Floyd, NPR, or other talk radio programming.

Part 6: Viewers' feedback on the *Monster of the Milky Way* website

After completing the NOVA program evaluation, participants in the *viewing* group were requested to visit *the Monster of the Milky Way* website on the PBS.org site http://www.pbs.org/wghh/nova/blackhole/ at their convenience within a two-week period. At the conclusion of the two-week period, they were asked to provide feedback on the website and to reflect on what they did at the site. The evaluation found that viewers generally visited at least one section of the site, explored at least one link, and had in-depth feedback to offer on their experience using the website, as follows:

⊃ The amount of time viewers spent visiting the site ranged from a low of 2 minutes to a high of 120 minutes, with the average for the group being 33 minutes. Two subgroup differences were found however. First, adults reported spending more time on the website than did youth (39.0 vs. 26.5 minutes, mean ratings). Also more frequent viewers of PBS programs reported spending more time on the website than did less frequent viewers (43.0 vs. 27.0 minutes, mean ratings).

⊃ The most frequently visited section of the site was *Birth of Black Hole*, visited by three-quarters of the group (75%). This was followed closely by *Tiny Black Holes* and *Catalogue of the Cosmos* (71% each) and then *Black Holes Explained* (68%). Somewhat less frequently visited were *Inside an Enigma* (57%) and *Galactic Explorer* (54%).

⊃ The most frequently visited links were *NASA's Imagine the Universe!*, visited by just under one-third (29%) of the group, followed closely by *Death Star* (27%) and *Runaway Universe* (26%). Other links were visited by less than one-quarter of the participant group as follows: Black *Holes: Gravity's Relentless Pull* (23%), *Introduction to Black Holes* (23%), and *Amazing Space* (18%).

⊃ When asked to describe what, if anything, they liked about the website and then to explain why they liked each thing, two-fifths (39%) of the viewers, slightly more adults than youth, said they liked the layout or format of the website, most often describing it as *well organized, easy to navigate*, and/or *having a clean design*. One-quarter (26%) of the viewers, about the same number of adults and teens, liked the graphics and other visuals featured on the website, most often describing them as amazing, *beautiful*, and/or *informative*. One-fifth of the viewers (20%), about two-thirds adults, liked the opportunity to hear the scientists talk about their work and/or about black holes. Not quite one-fifth of the viewers (17%), about the same number of youth and adults, appreciated the links to other resources or additional information. One-sixth (16%) of the viewers, about the same number of adults and youth, liked that the website was informative and contained in-depth information that supplemented content presented in the television program.

⊃ When asked to describe what, if anything, they disliked about the website, very few viewers pointed to anything they disliked about the site, with only a few youth (4%) describing the site as generally boring or dull and a couple of youth (2%) describing the website as lacking animation.

19

◆ Using scales of 1 to 7 viewers indicated they generally liked the *Monster of the Milky Way* website (mean, 5.7) and thought it provided interesting content (mean, 5.3). In their explanation of their ratings, a few adults praised the website content, most often noting that they found the subject matter interesting.

◆ Viewers generally agreed that the website was visually exciting (mean, 5.6). Several adults and youth praised the website's visual qualities, most often noting that they were interesting, colorful, exciting and/or helped them to understand the subject matter presented. Several viewers, almost all adults, pointed to something about the program's visuals that they disliked. In these cases viewers indicated they felt the visuals were *simplistic, unstimulating, too small,* or *lacking detail overall.*

◆ Using scales of 1 to 7, viewers generally agreed that the website offered a clear presentation (mean, 5.9) and that the website was easy to use (mean, 6.0). One subgroup difference was found in this case as adult viewers rated the website's ease of use higher than did youth.

◆ Viewers also generally agreed that it was easy to locate information that interested them on the website (mean, 5.9). One subgroup difference was found for this item as more frequent viewers of science/nature programs rated the website higher on this feature than did less frequent viewers.

◆ Using scales of 1 to 7, where a rating of 4 indicated "about right" viewers generally agreed that the website offered about the right amount of information (mean, 4.3), science (mean, 4.3), and interaction (mean 3.9).

◆ When asked to describe the most interesting things they learned from the website, just over two-fifths (43%) of the participants, about an equal number of adults and youth, discussed learning new information about black holes. Most often they focused on learning about mini-black holes or more in-depth information about black holes relating to their role in the universe, how they form, how they are studied, and how they work. A few participants also mentioned learning about astronomy more broadly. While most participants didn't specify areas of the site where they learned this information, a few did, pointing to *Catalogue of the Cosmos.* One-fifth (20%) of the viewers, almost all adults, enjoyed learning about the scientists featured in the scientist interviews, particularly relating to their discoveries or their views and lives as a scientist. Most often they praised Andrea Ghez's interview, and the information she presented about her work and how she became a scientist. Steve Ritz was also mentioned by a couple of viewers. One-fifth (20%) of the viewers, about an equal number of adults and youth, felt they learned from the visual elements of the site, particularly the slideshow and other images offered on the site. A handful of participants (6%), including a combination of adults and teens, said they enjoyed the teacher resources. Several youth (8%) said they enjoyed learning about NOVA/TV schedule information provided on the website. A couple of youth (2%) were interested in career information they gleaned from the website as in: *Girls in a male career. How to get there.* Several viewers (9%) commented that they didn't learn anything new of interest from the website, most often noting that the website didn't seem to them to offer more than they already learned from the program.

◒ Using scales of 1 to 7, viewers generally agreed that the website further increased their understanding of black holes (5.7 mean rating) as well as their curiosity (mean rating, 5.4). Adults rated their increase in understanding and curiosity higher than did youth. More frequent viewers of science/nature programs also rated their increase in understanding higher than did less frequent viewers. Several adults explained their ratings noting that it reinforced the content of the program and was a good companion to it. Several more appreciated the opportunity to be able to find in-depth information and address questions they had from viewing the program. Many viewers, mostly adults, specifically commented that the website increased their curiosity to learn more about black holes. Several adults felt their curiosity wasn't increased, however, and explained their individual reasons, including: lack of interest, lack of personal relevance, preference for the television program over the website, or difficulty in correlating the website and television program.

Final Remarks

Taken together, the above findings demonstrate that the *Monster of the Milky Way* NOVA program appealed to the 101 viewers recruited for the evaluation and had a significant impact on their knowledge of and beliefs about black holes and black hole research. These viewers generally liked the program, felt the storytelling was engaging, thought the content was interesting, and agreed that the program was visually exciting, clear, and struck the right balance in terms of the amount of information, science, and science principles provided.

While no significant gender differences were found among the evaluation findings, numerous other subgroup differences emerged. Most notably, many age group differences were found, particularly concerning the program's perceived appeal, clarity, and motivational value, as well as its overall educational impact. Adults tended to assign *Monster of the Milky Way* higher ratings than did youth and they generally scored higher on the 27 point assessment designed to evaluate viewers' learning gains from the program. Similarly, those reporting higher levels of knowledge of and interest in astronomy tended to score higher on the assessment than did those reporting lower levels of knowledge and interest, yet interestingly, these individuals didn't generally rate the program more favorably. Conversely, more frequent viewers of PBS tended to rate the program more favorably than did less frequent viewers, at least with respect to content appeal, visual excitement, storytelling, and clarity, yet did not outperform less frequent viewers on the content assessment.

Despite these varied subgroup differences, overall *Monster of the Milky Way* was still generally well received by and successful with individuals of varying ages, television viewing habits, and knowledge of and interest in astronomy. As noted at the outset of the report, the participant group as a whole had little prior familiarity with astronomy and black holes in particular, and was not predominately comprised of committed PBS and science/nature viewers, but rather a combination of regular and occasional viewers of these programs. This wide range of television viewing habits represented in the sample, however, neither diminished the overall appeal of *Monster of the Milky Way* nor its success in achieving its goals. The program addressed many difficult and abstract science concepts, yet was still enjoyed by and successful with a diverse viewing audience, one that extended beyond the traditional PBS viewer, science/nature show enthusiast, or astronomy buff.

Knight-Williams Research Communications

Beyond the immediate impact of the program, the evaluation also found that *Monster of the Milky Way* continued to influence viewers more than two weeks after viewing. The majority of viewers reported they were still thinking about some aspect of the program; more than half said that they had discussed the program with friends, family, or co-workers; and roughly a third had either seen something on TV, read something in a magazine, book, or online, or heard something on the radio that reminded them of the program.

Finally, the evaluation further found that the *Monster of the Milky Way* website met the project's goal of deepening and supplementing viewers' learning from the television program. Viewers overwhelmingly found the website to be appealing, clear, and usable; were able to articulate how it supplemented their learning about black holes after watching the NOVA program; and felt it increased their understanding of and curiosity about black holes.

PUBTV/ONLINE

Carriage Analysis	Metered Grids	Sweep Analysis	News & Forums
Cable Analysis	Metered Reports	Sweep Reports	Home

Provided by TRAC Media Services

Metered Grids

Metered Show Report

Nova [Compare This Time]
Monster of the Milky Way - #3314
Oct 31, 2006
Primary Station Report   All Stations (go)   GRP Report   Download

Station	Market	Rank	Start Time	Rtg	Shr
KOPB	Portland OR	23	8:00 PM	4.9	8
WNED	Buffalo NY	49	8:00 PM	4.1	6
KPBS	San Diego CA	27	8:00 PM	4.1	6
KUED	Salt Lake UT	35	7:00 PM	3.7	7
KCPT	Kansas City MO	31	7:00 PM	3.2	5
WMVS	Milwaukee WI	34	7:00 PM	3.0	5
KVIE	Sacramento CA	20	8:00 PM	2.8	5
WKNO	Memphis TN	44	7:00 PM	2.8	4
WQED	Pittsburgh PA	22	8:00 PM	2.7	4
WVIZ	Cleveland OH	17	8:00 PM	2.6	4
KCTS	Seattle WA	14	8:00 PM	2.5	4
KLVX	Las Vegas NV	43	8:00 PM	2.4	4
KERA	Dallas TX (LPM)	8	7:00 PM	2.4	4
WTTW	Chicago IL (LPM)	3	8:00 PM	2.3	4
WGCU	Fort Myers FL	64	8:00 PM	2.3	3
WHRO	Norfolk VA	42	8:00 PM	2.2	3
KLRN	San Antonio TX	37	8:00 PM	2.2	4
KNME	Albuquerque NM	45	8:00 PM	2.2	3
KRMA	Denver CO	18	7:00 PM	2.1	3
WOSU	Columbus OH	32	8:00 PM	2.1	3
WJCT	Jacksonville FL	50	8:00 PM	2.1	3
WNPT	Nashville TN	30	7:00 PM	2.1	3
KETA	Oklahoma OK	45	7:00 PM	2.0	3
WNET	New York NY (LPM)	1	8:00 PM	2.0	3
KTCA	Minneapolis MN	15	7:00 PM	2.0	4
WMFE	Orlando FL	19	8:00 PM	1.9	3
KETC	St. Louis MO	21	8:00 PM	1.8	3
WFYI	Indianapolis IN	25	8:00 PM	1.7	3
KQED	San Francisco CA (LPM)	5	8:00 PM	1.7	3
KCET	Los Angeles CA (LPM)	2	8:00 PM	1.7	3

259

WTVS	Detroit MI (LPM)	11	8:00 PM	1.7	3
WBIQ	Birmingham AL	40	7:00 PM	1.7	3
WGBH	Boston MA (LPM)	7	8:00 PM	1.7	3
WCET	Cincinnati OH	33	8:00 PM	1.6	3
KAET	Phoenix AZ	13	8:00 PM	1.6	3
KOED+	Tulsa OK	62	7:00 PM	1.6	3
WCVE	Richmond VA	61	8:00 PM	1.6	2
WHYY	Philadelphia PA (LPM)	4	8:00 PM	1.5	2
WUNC	Raleigh Durham NC	29	8:00 PM	1.4	2
WGTV	Atlanta GA (LPM)	9	8:00 PM	1.4	2
WKOP	Knoxville TN	60	8:00 PM	1.4	2
KLRU	Austin TX	52	7:00 PM	1.3	3
WEDH+	Hartford CT	28	8:00 PM	1.3	2
WKMJ	Louisville KY	48	8:00 PM	1.1	2
WXEL	West Palm Beach FL	38	8:00 PM	1.1	2
KAET	Phoenix AZ	13	11:00 PM	1.1	3
KVIE	Sacramento CA	20	11:00 PM	0.8	3
WPBT	Miami FL	16	8:00 PM	0.7	1
WUNL	Greensboro NC	47	8:00 PM	0.7	1
WRET	Greenville SC	36	8:00 PM	0.4	1
WUNG	Charlotte NC	26	8:00 PM	0.4	1

Avg:	2	3
Top 6 Avg:	2	3.2
Weighted Avg:	2	

* The standard broadcast day is 6am - 6am. Because the Nielsen day runs 2am - 2am, the GRPs for yesterday run 6am-2am. All other days are 6am - 6am.

The following markets switched to LPM data as of: BN: 4/25/2002, NY: 4/8/2004, LA: 4/29/2004, CH: 7/8/2004, SF: 9/30/2004, DC: 6/30/2005, PH: 6/30/2005, DE: 1/5/2006, DL: 1/5/2006, AT: 6/29/2006

260

THE OTHER SIDE OF INFINITY

BLACK HOLES

DENVER MUSEUM OF NATURE & SCIENCE

FOR IMMEDIATE RELEASE

Julia Taylor   Laura Holtman
(303) 370.6384   (303) 370.6407
julia.taylor@dmns.org   laura.holtman@dmns.org

BLACK HOLES: THE OTHER SIDE OF INFINITY Collaborator Biographies

NARRATOR: LIAM NEESON
Liam Neeson continues to take on challenging roles and has become one of the leading international motion-picture actors today. The Irish-born Neeson originally sought a career as a teacher, attending Queens College, Belfast, and majoring in physics, computer science, math and drama. His interest quickly shifted to theater, and in 1976 Neeson began his acting career with the prestigious Lyric Players Theatre in Belfast.

Neeson is recognized for his many memorable roles. He starred in the box-office phenomenon *Star Wars: Episode I—The Phantom Menace* (1999), playing the role of Qui-Gon Jinn, the Master Jedi Knight who bestows his Force-ful wisdom upon Obi-Wan Kenobi and the young Anakin Skywalker. In addition, Neeson was nominated for an Academy Award for his portrayal of Oskar Schindler in Steven Spielberg's highly acclaimed *Schindler's List*, and has appeared in other recent hits such as *Batman Begins, Kinsey* and *Love Actually*.

COMPOSER: RICHARD FIOCCA
Composer Richard Fiocca has a long list of award-winning film and television credits, including scores for PBS, HBO, the BBC, and all the major US networks. Recent work includes theme and scoring for the CBS newsmagazine *48 Hours*, the Discovery Channel/Animal Planet's *Into the Lion's Den*, the IMAX feature *Wildfire*, and music and sound design for the Oscar winning HBO documentary *Liberation: A Survivor Remembers*. He also composed the score for CBS TV's groundbreaking special on the World Trade Center attack *9/11*. Recent collaborations with Thomas Lucas include *Mysteries of Deep Space* and *Voyage to the Milky Way*, both for PBS.

Fiocca has also created an extensive oeuvre of concert works: his *String Quartet No. 1 in D* was performed at the Kennedy Center in Washington, DC, and his *Serenade for Clarinet* was recently featured at the Contemporary Composer's Concert at Carnegie Hall. He is currently working on *The Fourth Way*, an orchestral tone poem based on the life and teachings of the Russian mystic and spiritualist G.I. Gurjieff.

A frequent visitor to Prague as both a conductor and composer, Fiocca recorded the score for *Black Holes: The Other Side of Infinity* with the Czech Screen Orchestra.

DIRECTOR: THOMAS LUCAS
Thomas Lucas has completed more than 20 major documentary films for *NOVA*, PBS, the Discovery Channel and other networks. He specializes in productions that make use of special effects and high-end computer animations.

Lucas got his start in 1985 with the production of a documentary for *NOVA* called "Tornado!" The film became one of the most popular productions in *NOVA*'s history, reaching an audience of tens of millions. It was also cited by Michael Crichton as the inspiration for the 1996 motion picture *Twister*. Lucas' other productions have explored such diverse subject matter as the mysteries of deep space, cannibalism, cyborgs, the 1988 Yellowstone wildfires and hammerhead sharks, among other topics.

Black Holes: The Other Side of Infinity is Lucas' first planetarium show. Using adaptations of the scientific visualizations from *Black Holes*, Lucas is directing a *NOVA* program called "Monster of the Milky Way" that will be broadcast on PBS in 2006.

-MORE-

EXECUTIVE PRODUCER: JOSLYN SCHOEMER

Schoemer was bitten by the astronomy bug in 1990 when attending a lecture about wormholes and black holes. After receiving her undergraduate degree in astrophysics and math, she discovered a passion for sharing the excitement of astronomical discoveries and the exploration of space with the general public through films, exhibits and educational programs. She received a M.S. in museum and field studies, with an emphasis on informal science education.

Schoemer has worked on a variety of space science education projects for informal learning institutions. These include exhibits and programs at the Smithsonian's National Air and Space Museum in Washington, DC, including *Voyage*, a scale-model solar system permanently installed on the National Mall. She coordinated space projects for the Challenger Center for Space Science Education, the University of Colorado Natural History Museum and the University of Colorado's Fiske Planetarium. Schoemer joined the Denver Museum of Nature & Science in 1999 as a project manager and worked on developing the Museum's permanent space science exhibition, *Space Odyssey*. *Black Holes: The Other Side of Infinity* is her first all-digital planetarium show.

SCIENCE DIRECTOR: DR. ANDREW J.S. HAMILTON

Dr. Andrew J.S. Hamilton is a fellow of JILA (formerly the Joint Institute for Laboratory Astrophysics), and a professor in the Department of Astrophysical and Planetary Sciences at the University of Colorado at Boulder, where he has worked since 1986.

Though Hamilton's background is in mathematics and astrophysics and he has published about 60 papers on subjects ranging from supernovas to cosmology, his students helped pique his interest in black holes. Their strong desire to understand relativity led Hamilton to develop his first scientifically accurate general relativistic visualizations of black holes in 1996. With the help of one of his accelerated introductory astronomy classes, Hamilton used those visualizations to create a highly popular show on black holes that debuted at Fiske Planetarium at CU in 1997. This content was adapted for a Web page called "Falling Into a Black Hole," which has received more than a million visitors since it went online in 1997.

Hamilton continued to refine his visualization technique with the development of the "Black Hole Flight Simulator" during a yearlong sabbatical with the Denver Museum of Nature & Science in 2001 and 2002. The simulator, an elaborate software program, takes real computational data about black holes and translates it into the images that are the centerpiece of *Black Holes: The Other Side of Infinity*.

SCIENCE DIRECTOR: DR. LYNN COMINSKY

Dr. Lynn Cominsky has been a professor of physics and astronomy at Sonoma State University since 1986, and currently chairs the Departments of Physics and Astronomy, and Chemistry. At SSU, she also directs the education and public outreach (E/PO) group that develops science and mathematics curriculum resources for grades K–12, and is primarily sponsored by NASA.

Cominsky is a scientific coinvestigator and leads the education and public outreach team for the Swift Gamma-ray Burst Explorer Mission, launched by NASA on November 20, 2004, and featured in *Black Holes: The Other Side of Infinity*. Swift is studying gamma-ray bursts, the biggest explosions observed in the universe today. Cominsky serves in a similar capacity on NASA's Gamma-ray Large Area Space Telescope (GLAST) mission (expected to launch in 2007), and on the European Space Agency's XXM-Newton mission, which studies X-rays from black holes, neutron stars, supernova remnants and stellar corona.

NCSA PRODUCER AND ART DIRECTOR: DONNA J. COX

Donna J. Cox is a professor of art and design at the University of Illinois at Urbana-Champaign and director of visualization at the National Center for Supercomputing Applications. Her collaborative scientific visualizations are featured in a variety of large-format venues around the world, including the Academy Award-nominated 1997 IMAX film *Cosmic Voyage*, and on two American Museum of Natural History planetarium shows, *Passport to the Universe* and *The Search for Life: Are We Alone?* She and her team also provided the thrilling visuals used in the *NOVA* programs "Hunt for the Supertwister" and "Runaway Universe" on PBS.

Cox's passion is bringing cultural scientific narratives to a wide range of audiences through innovative and aesthetic presentations of data-driven scientific simulations. In addition to her large-scale productions, Cox has authored many articles on the use of visualization in science, art, and information design.

###

DMNS-05-101

THE OTHER SIDE OF INFINITY
BLACK HOLES

DENVER MUSEUM OF NATURE&SCIENCE

Julia Taylor   Laura Holtman
(303) 370.6384   (303) 370.6407
julia.taylor@dmns.org   laura.holtman@dmns.org

The History of BLACK HOLES: THE OTHER SIDE OF INFINITY

Black Holes: The Other Side of Infinity breaks new ground in its content and its approach to visualizing real science. Behind this remarkable achievement is a team of talented people, collaborators who married their unique specialties and capabilities to create a final show that is much greater than the sum of its parts.

A number of factors led to the production of the show. As part of an ambitious overhaul of its facility that began in 2000, the Denver Museum of Nature & Science initiated a radical redesign of one of its mainstay attractions, Gates Planetarium. Construction crews rebuilt the planetarium from the ground up. The old reclining seats were replaced with stadium seats, the dome was tilted to surround the audience with the picture, and engineers installed a 20-channel sound system and 11 state-of-the-art digital projectors. This system projects more than one million pixels onto the dome, producing ultra-high resolution images and vivid colors that are beyond compare. The new Gates Planetarium opened in the summer of 2003 and remains one of the best immersive digital dome theaters in the world.

While construction on the planetarium was underway, the need for strong scientific and educational content to display in it became clear. In 2001, the Museum approached Dr. Andrew J.S. Hamilton, a professor in the Department of Astrophysical and Planetary Sciences at the University of Colorado at Boulder, about creating something that might work. For several years, Hamilton had been perfecting simple animations of black holes based on the equations of Albert Einstein's general theory of relativity. But now he wanted to create something far more detailed and spectacular. The concept of the Black Hole Flight Simulator was born. During a yearlong sabbatical at the Museum in 2001 and 2002, Hamilton wrote and refined this unusual piece of software, which now has more than 100,000 lines of code.

The Black Hole Flight Simulator does something that has never been attempted before. It takes the real, computational science of black holes, and translates it into accurate images. "At the start, I had little idea of what the insides of black holes would look like—I don't think anyone had much idea," said Hamilton. "But as he worked on his software, a clear and beautiful picture emerged. "It has been a thrill to see art emerging from Einstein's equations," he said.

The idea of taking the Black Hole Flight Simulator and using it to create a show for Gates Planetarium gained momentum when an independent documentary producer named Thomas Lucas got involved. Lucas had some exciting news when he approached Hamilton: NASA's Gamma-ray Large Area Space Telescope (GLAST) mission was willing to provide some seed money for a planetarium show about black holes, and the well-respected PBS science show *NOVA* was also interested in developing a program about the subject.

For Lucas, making a show about black holes was something he had been thinking about for a long time, so he leapt at the chance to do it. "As a filmmaker, I know that every project I really believe in has its beginnings in a single moment in time," he said. "That moment for *Black Holes: The Other Side of Infinity* was on a day in June 1994. I unfolded the newspaper and read that scientists had used the newly christened Hubble Space Telescope to peer into the center of an immense nearby galaxy known as M87. There they found a supermassive black hole weighing in at 4 billion times the mass of our sun. Even as a sci-fi fan, I had never imagined anything like this."

-MORE-

The pieces were starting to come together—a state-of-the-art planetarium; an intriguing and educational subject to explore; stunning, unusual visuals; and an experienced director who wanted to do the project. Now all that was needed was more money and the right people to make the show a reality.

Using its clout as an institution devoted to informal science education, the Denver Museum of Nature & Science applied for a grant from the National Science Foundation to support the project. The effort paid off handsomely. The NSF awarded $1.2 million to the Museum and its collaborators to produce the show that would eventually become *Black Holes: The Other Side of Infinity.*

Rounding out the team of collaborators is a visualization team from the National Center for Supercomputing Applications at the University of Illinois at Urbana-Champaign led by professor Donna Cox. Lucas has worked with the NCSA team on several of his previous science documentaries, including the award-winning NOVA productions "Runaway Universe" and "Hunt for the Supertwister."

Cox and her team are widely known as pioneers in visualizing scientific data and supercomputer simulations using high-end graphical techniques. Drawing on NSF-funded computing resources at the NCSA, the team managed multiple terabytes of data to create the beautiful, scientifically accurate images for *Black Holes: The Other Side of Infinity.*

"Most of the production group was accustomed to designing programs for the television screen. The dome is a fundamentally different experience," said Joslyn Schoemer, the executive producer of *Black Holes: The Other Side of Infinity.* "For this project, we optimized every frame of the show for the hemispherical screen. We evaluated the composition of every shot and edited the show to maximize the viewer experience of 'being there.' This extraordinary effort ensures that the audience is surrounded and participating in the action."

In addition to NCSA and its team of visualization specialists, *Black Holes: The Other Side of Infinity* drew on the talents of scientific advisors, graphic artists, writers, a planetarium operations team, composers, sound designers, cinematographers and educators. In charge of distribution is Spitz, Inc., a planetarium manufacturing company with experience marketing planetarium shows across the world. Of course, having actor Liam Neeson agree to contribute his commanding voice to the project was a coup for the production team, and an essential element to bring the show alive for audiences. The original score composed by Richard Fiocca provides an elegant finishing touch.

The entire production process took three years to complete, and now that the show has taken shape, the crew is excited with the final product. Director Lucas describes the production as "a wonderful collaboration in which the guiding principle was creating the highest quality show we knew how."

"*Black Holes: The Other Side of Infinity* is for me the culmination of a dream many years in the making," said Hamilton. "The show marries science and art in a new way that compromises neither. In particular, the show breaks new ground in visualizing accurately what Einstein's equations predict about what really happens inside black holes. What actually happens looks nothing like, but is at least as fantastic as, any Hollywood rendering."

###

NEWS
RockyMountainNews.com

HOME   NEWS ▼   BUSINESS ▼   SPORTS ▼   RECREATION ▼   OPINION ▼   SPOTLIGHT ▼   WEB EXTRA ▼   JOBS ▼   AUTOS ▼   HOMES ▼   CLASSIFIEDS ▼   SHOP ▼

HOME › NEWS › LOCAL

Shedding light on black holes

By Jim Erickson, Rocky Mountain News
February 1, 2006

Now you can journey to the core of a voracious black hole without leaving Denver.

A new planetarium show produced by the Denver Museum of Nature & Science leads viewers into the immense black hole astronomers say is lurking at the center of our Milky Way galaxy.

The 23-minute production features the first scientifically accurate visualizations of black holes — images based on Albert Einstein's equations and hard observational data, researchers involved with the project said Tuesday.

"This is the coolest I've ever gotten to a black hole or would ever want to get," said Sonoma State University astronomer Lynn Cominsky, who has been studying black holes for more than 30 years.

Cominsky and University of Colorado astrophysicist Andrew J.S. Hamilton are the program's science directors.

"This does represent the absolute best of our knowledge," Cominsky said after the show, narrated by actor Liam Neeson, was previewed for reporters. Black Holes: The Other Side of Infinity opens Feb. 10 at the museum's Gates Planetarium.

Perhaps the most arresting sequence of images in the new program shows a black hole forming after a red supergiant star explodes.

The scene begins with the fiery-orange sphere of the supergiant hovering above a blue gridwork meant to represent the fabric of space-time. Einstein predicted that a massive object's gravitational force can warp space-time and that the formation of a black hole can puncture it.

In Black Holes, the supergiant explosion creates a tornado-like vortex in the blue gridwork's surface.

As the viewer is drawn ever closer, the whirlpool becomes a raging river with hard-paddling kayakers. They struggle to avoid plunging over the edge of a Niagara-size waterfall.

But resistance proves futile, and the kayakers turn swept into the black hole.

"How do we know it's right?" Hamilton said of the show's visualizations. "You follow the laws of physics, and in this case it's the laws of general relativity laid down by Einstein."

To create images for the digital planetarium's dome, the production team relied on the Black Hole Flight Simulator, a computer program devised by Hamilton during a yearlong sabbatical at the museum in 2001 and 2002.

The simulator was a follow-up to black hole visualizations Hamilton began in the 1990s.

Armed with Hamilton's software, computer graphics experts at the National Center for Supercomputing Applications in Illinois developed the show's eye-popping images.

The program takes viewers on a fast-paced tour of black holes across deep space. Along the way, they glimpse the creation of the universe, the formation of the first stars, a collision between two galaxies, and a stellar explosion called a supernova.

The supernova visuals required 5,400 hours of supercomputer time, said Donna Cox, the show's producer and art director. The Illinois supercomputer center generated 750 gigabytes of digital imagery for Black Holes, said Cox, director of visualization there

Digital image © The Board of trustees of the University of Illinois

Scientists believe black holes lie at the center of the Milky Way galaxy. A show, Black Holes: The Other Side of Infinity, leads viewers into the dark regions of space. The show, produced by the Denver Museum of Nature & Science, opens Feb. 10 at the museum's Gates Planetarium.

STORY TOOLS
Email this story | Print

265

A black hole is an unimaginably dense object, with a gravitational field so strong that nothing - not even light - can escape its pull.

Because they can't be observed directly, black holes must be inferred from their effects on nearby matter. A recent flurry of black hole discoveries has nearly all astronomers convinced that the long-theorized objects truly exist, Cominsky said.

There are two types of black hole.

Stellar black holes form when a large, dying star explodes. The star's outer layers are blasted away, but its inner core can collapse into a black hole holding a few times the mass of the sun.

Our Milky Way galaxy probably holds millions of stellar black holes.

Supermassive black holes lurk in the center of galaxies. They can be millions - even billions - of times more massive than the sun and can shred neighboring stars that get too close.

If you go

• Where: Denver Museum of Nature & Science, 2001 Colorado Blvd.

• When: Opens Feb. 10.

• Tickets: Adults, $15 (all tickets include admission to museum); 18 and under, $10, 65 and older, $10. For museum members, planetarium show is $5, $4 for 18 and under and 65 and over.

• For specific show times and to watch a trailer of the film, go to: www.dmns.org

DENVERPOST.com

April 23, 2006
Denver, CO

Denver Post, The (CO)

Black holes get turned inside out CU astronomer's work with planetarium a scientific thrill-ride

February 1, 2006
Section: DENVER AND WEST
Page: B-01
  Katy Human

Denver Post Staff Writer

In a 1992 episode of the cartoon Ren & Stimpy, a black hole sucks up the characters' spaceship and hurls it onto the surface of a very strange planet.

Clouds float by in psychedelic shapes. Ren's eyes slip off his head, Stimpy's nose comes off on his finger.

"It's a beautiful, artistic interpretation of black holes, which warp everything," said University of Colorado astronomer Andrew Hamilton, who studies black holes. "I loved it."

Hamilton's own vision is different.

The physicist started with Einstein's theory of general relativity - a set of 100-year-old equations that suggested black holes could exist - and used mathematics to paint a realistic portrait of the inside of one of space's most intriguing objects.

Exploding stars can form black holes that create such a strong gravitational pull that not even light can escape.

The results of Hamilton's and his colleagues' two-year effort will go on display Feb. 10 at the Denver Museum of Nature & Science, in one of the most scientifically accurate planetarium shows developed.

"Black Holes: The Other Side of Infinity" was produced by the museum, Hamilton and independent director Thomas Lucas, from New York. Actor Liam Neeson narrated the show, which will be offered to international audiences after a Denver debut.

267

"In the planetarium world, it's a megabuster," said Joslyn Schoemer, a Denver Museum project manager and executive producer of the show.

The 23-minute planetarium production and a related NOVA television show were funded in part by $1.5 million in grants from the National Science Foundation and NASA.

The show is a vertigo-inducing mindblower, with an astonishingly detailed - and accurate - fly-through of the Milky Way Galaxy. Stars explode in black-hole generating supernovas. Nebulas are born. Kayakers are pulled down a black-hole-like waterfall.

It took weeks to generate sequences on powerful supercomputers, said art director Donna Cox, a researcher at the National Center for Supercomputing Applications at the University of Illinois at Urbana-Champaign.

"We are all filled with anticipation," said Neil deGrasse Tyson, director of the Hayden Planetarium at the American Museum of Natural History in New York.

The Hayden is one of a few dozen U.S. planetariums technically capable of running Denver's new show. The Denver museum has twice leased Hayden-produced shows, Schoemer said, but the opposite has never happened - yet.

Lucas, the show's director, said Hamilton is "completely obsessed - obsessed with general relativity and the equations of Einstein."

What Hamilton did that was new was to ask what Einstein's equations said about black holes' interiors. Many scientists, authors and artists have depicted what it might be like to be caught on the edge of a black hole's relentless pull.

But what happens once space falls inside, spinning faster and faster as it approaches the unimaginably dense interior?

Objects spin around a center generate centrifugal force, Hamilton explained, which eventually counteracts the massive gravitational pull of the black hole's center. That can "fling material back out," where it collides spectacularly with material spinning into the black hole.

"It becomes violently unstable," Hamilton said. "And we believe that huge instability creates extremely hot plasma.

"And so you'd die," he said. "Vaporized."

268

References

Ackerman, J. (1985) *The Involvement of Artists in Renaissance Science*. In: Shirley, J. and Hoeniger, F. eds. *Science and the Arts in the Renaissance*. Washington D.C., Folger Shakespeare Library, pp. 94-129.

Adams, F. and Laughlin, G. (1999) *The Five Ages of the Universe: Inside the Physics of Eternity*. New York, Touchstone.

Ahl, V. and Allen, T. (1996) *Hierarchy Theory: A Vision, Vocabulary, and Epistemology*. New York, Columbia University Press.

Akerman, J. (2007) Finding Our Way. In: Akerman, J.R. and Karrow Jr., R.W. eds. *Maps: Finding Our Place in the World*. Chicago, University of Chicago Press, pp. 19-63.

Akerman, J. and Karrow Jr., R. (2007) *Maps: Finding Our Place in the World*. Chicago, University of Chicago Press.

Albers, J. (1963) *Interaction of Color*. New Haven, Yale University Press.

Alverson, H. (1991) Metaphor and Experience: Looking Over the Notion of Image Schema. In: Fernandez, J. ed. *Beyond Metaphor: The Theory of Tropes in Anthropology*. Stanford, Stanford University Press, pp. 94-117.

Anderson, C. (1989) Images Worth Thousands of Bits of Data: Computer Artist Transform Equations into Dramatic Simulations at Illinois. *The Scientist*, 3, pp. 1, 16-17.

Anderson, S., Drasdo, N., and Thompson, C. (1995) Parvocellular Neurons Limit Motion Acuity in Human Peripheral Vision. *Proceedings: Biological Sciences*, 261.1360, pp. 129-138.

Anonymous (2008) "FullDome" Digital Surround Theater Technology Ready to Explode into Special-Venue Markets. Blooloop.com [Internet], 31 May. Available from: < http://www.blooloop.com/PressReleases/-FullDome-Digital-Surround-Theater-Technology-Ready-to-Explode-into-Special-Venue-Markets/846> [Accessed 1 June 2008].

Arnheim, R. (1974) *Art and Visual Perception: A Psychology of the Creative Eye*. Berkeley, University of California Press.

Ascott, R. (1966-1967) Behaviorist Art and the Cybernetic Vision. In: Packer, R. and Jordan, K. eds. *Multimedia: From Wagner to Virtual Reality*. New York, W. W. Norton & Company, pp. 95-103.

Ascott, R. (1968) The Cybernetic Stance: My Process and Purpose. *Leonardo*, 1, pp. 105-112.

Ascott, R. (1994) The Architecture of Cyberception. In: Ascott, R. ed. *Telematic Embrace: Visionary Theories of Art, Technology, and Consciousness*. Berkeley, University of California Press, pp. 319-339.

Ascott, R. (2003) *Telematic Embrace: Visionary Theories of Art, Technology, and Consciousness*, Berkeley, University of California Press.

Ascott, R. (2006) Technoetic Pathways Toward the Spiritual in Art: A Transdisciplinary Perspective on Connectedness, Coherence and Consciousness. *Leonardo*, 39.1, pp. 63-69.

Auger, P. (1989) *Dynamics and Thermodynamics in Hierarchically Organized Systems: Applications in Physics, Biology and Economics*. Oxford, Pergamon Press.

Bagrow, L. and Skelton, R. (1985) *History of Cartography*. Chicago, Precedent.

Baigrie, B. (1996) *Picturing Knowledge: Historical and Philosophical Problems Concerning the Use of Art in Science*. Toronto, University of Toronto Press.

Balaram, S. (1995) Product Symbolism of Gandhi and its Connection with Indian Mythology. In: Margolin, V. and Buchanan, R. eds. *The Idea of Design: A Design Issues Reader*. Cambridge, MA, The MIT Press, pp. 127-143.

Barlow, C. (1991) *From Gaia to Selfish Genes: Selected Writings in the Life Sciences..* Cambridge, MA, The MIT Press.

Beck, J. (1966) Effect of Orientation and of Shape Similarity on Perceptual Grouping. *Perception and Psychophysics*, 1, pp. 300-302.

Benjamin, W. (1978) *Reflections: Essays, Aphorisms, Autobiographical Writings*. New York, Schocken Books.

Benjamin, W. (1979) *One-Way Street and Other Writings*. London, Verso.

Berger, J. (1977) *Ways of Seeing*. New York, Penguin Books.

Berger, M. and Oliger, J. (1984) Adaptive Mesh-Refinement for Hyperbolic Partial Differential Equations. *Computational Physics*, 53, pp. 484-512.

Berlin, B. and Kay, P. (1969) *Basic Color Terms: Their Universality and Evolution*. Berkeley, University of California Press.

Bermudez, J., Agutter, J., Foresti, S., Westenskow, D., Syroid, N., Drews, F., and Tashjian, E. (2005) Between Art, Science and Technology: Data Representation Architecture. *Leonardo*, 38, pp. 280-285.

Bertin, J. [1967] (1983) *Semiology of Graphics: Diagrams, Networks, Maps*. Translated from the French by W. Berg. Madison, The University of Wisconsin Press.

Berton Jr., J. (1990) Film Theory for the Digital World: Connecting the Masters to the New Digital Cinema. *Leonardo Digital Image: Digital Cinema Supplemental*

Issue, pp. 5-11.

Beshers, C.and Feiner, S. (1994) Automated Design of Data Visualization. In: Rosenblum, L., Earnshaw, R., Encarnacao, J., Hagen, H., Kaufman, A., Klimenko, S., Nielson, G., Post, F. and Thalmann, D. eds. Scientific Visualization Advances and Challenges. San Diego, Academic Press, pp. 87-102.

Bierlein, J. (1994) *Parallel Myths*. New York, Ballantine.

Birren, F. (1978) *Color and Human Response*. New York, Van Nostrand Reinhold.

Black, J. (1997) *Maps and History: Constructing Images of the Past*. New Haven, Yale University Press.

Black, M. (1962) *Models and Metaphor*. Ithaca, Cornell University Press.

Blakemore, C. (1973) The Baffled Brain. In: Gregory, R. and Gombrich, E. eds. *Illusion in Nature and Art*. New York, Charles Scribner's Sons, pp. 9-47.

Bonneau, G. (1998) Multiresolution Analysis on Irregular Surface Meshes. *Visualization Proceedings*, 4, pp. 365-378.

Boslough, J. (1985) *Stephen Hawking's Universe*. New York, Quill/William Morrow.

Boudourides, M. (2003) Constructivism, Education, Science, and Technology [Internet]. *Canadian Journal of Learning and Technology*, 29.3. Available from: <http://www.cjlt.ca/index.php/cjlt/article/view/83/77> [Accessed 18 December 2008].

Bowman, D. and McMahan, R. (2007) Virtual Reality: How Much Immersion is Enough? *Computer: Innovative Technology for Computer Professionals*, 40, pp. 36-43.

Bradie, M. (1999) Science and Metaphor. *Biology and Philosophy*, 14, pp. 159-166.

Brown, J. (1996) Illustration and Inference. In: Baigrie, B. ed. *Picturing Knowledge: Historical and Philosophical Problems Concerning the Use of Art in Science*. Toronto, University of Toronto Press, pp. 250-268.

Brown, M. (2002) iGrid : International Networking Conference, 23-26 September 2002, Amsterdam, Nederland. Available from: <http://www.igrid2002.org/PROPOSALS/appPhys_astroVis.html> [Accessed 18 December 2008].

Brown, M. (Maxine@evl.uic.edu), 7 December 2008. Re: History of Computer Graphics. [unpublished document, 1989-90]. Email to D. Cox (cox@ncsa.uiuc.edu).

Brown, T. (2003) *Making Truth: Metaphor in Science*. Urbana-Champaign, University of Illinois Press.

Bruno, M., 20 October 2008. Venues Licensing Report: *Black Holes: The Other Side of Infinity*. [Spitz, Inc.]. To: Thomas Lucas Productions, DMNS, NCSA.

271

Bruno, M. (2008) [personal communication] Letter to D. Cox, 25 November.

Bryson, S. (1994) Real-Time Exploratory Scientific Visualization and Virtual Reality. In: Rosenblum, L., Earnshaw, R., Encarnacao, J., Hagen, H., Kaufman, A., Klimenko, S., Nielson, G., Post, F. and Thalmann, D. eds. *Scientific Visualization Advances and Challenges.* San Diego, Academic Press, pp. 65-85.

Buchwald, J. (1995) *Theories of Practice: Stories of Doing Physics.* Chicago, University of Chicago Press.

Bucke, R. (1993) *Cosmic Consciousness: A Study in the Evolution of the Human Mind.* New York, Carol Publishing.

Campbell, J. (1974) *The Mythic Image.* Princeton, Princeton University Press.

Card, S., Mackinlay, J. and Shneiderman, B. (1999) *Readings in Information Visualization: Using Vision to Think (Interactive Technologies).* San Francisco, Morgan Kaufmann.

Carr, H., Moller, T. and Snoeyink, J. (2001) Simplicial Subdivisions and Sampling Artifacts. In: *Proceedings Visualization 2001,* October 21-26, 2001, San Diego, CA. New Jersey, IEEE Computer Society, pp. 99-106.

Carruthers, P. (2007) Higher-Order Theories of Consciousness. In: *Stanford Encyclopedia of Philosophy.* Revised edition. Stanford, Stanford University Press.

Caudill, E. (1994) The Bishop-Eaters: The Publicity Campaign for Darwin and On the Origin of Species. *Journal of the History of Ideas, 55,* pp. 441-460.

Chang, K. (2000) Down on the Galactic Highway, a Head-On Collision Shapes Up. *New York Times / Science,* 9 May.

Chang, K. (2000) Astronomers Find a New Size of Black Hole. *New York Times / Science,* 13 September.

Chen, M., Hansen, C., Ma, K., North, C., and Carpendale, S. eds. (2008) *IEEE Transactions on Visualization and Computer Graphics Vis Week Proceedings,* 14.6, 2008, Columbus, OH. Los Alamitos, CA, IEEE Computer Society.

Chen, M., Townsend, P., and Vince, J. eds. (1996) High Performance Computing for Computer Graphics and Visualization. Proceedings of the International Workshop on High Performance Computing for Computer Graphics and Visualization. London, Spring-Verlag.

Chevreul, M.E. [1839] (1967) *The Principles of Harmony and Contrast of Colors.* New York, Reinhold.

Christ, C. (1997) *Rebirth of the Goddess: Finding Meaning in Feminist Spirituality.* New York, Routledge.

Cleveland, W. (1993) *Visualizing Data.* Lafayette, IN, Hobart Press.

Cohen, P.E. (2002) *Mapping the West: America's Westward Movement, 1524-1890.* New York, Rizzoli.

Cooper Jr., H. (2000) Sphere of Influence [Internet]. *Natural History,* 109.1. Available from: <http://findarticles.com/p/articles/mi_m1134/is_/ai_59210816> [Accessed 18 December 2008].

Cosgrove, D. (2007) Mapping the World. In: Akerman, J. and Karrow Jr., R. eds. *Maps: Finding Our Place in the World.* Chicago, University of Chicago Press, pp. 65-115.

Cox, D. (1988) Renaissance Teams and Scientific Visualization: A Convergence of Art and Science. *ACM/SIGGRAPH Conference Course #29: Collaboration in Computer Graphics Education,* pp. 81-104.

Cox, D. (1988) Using the Supercomputer to Visualize Higher Dimensions: An Artist's Contribution to Scientific Visualization. *Leonardo,* 21.3, pp. 233-242.

Cox, D. (1989) The Tao of Postmodernism: Computer Art, Scientific Visualization, and Other Paradoxes. ACM / SIGGRAPH '89 Art Show Catalogue, Computer Art in Context. *Leonardo Supplemental Issue,* pp. 7-12.

Cox, D. (1990) Scientific Visualization: Mapping Information. Australia, Australian Computer Graphics Association, pp. 101-106.

Cox, D. (1991) Collaborations in Art / Science: Renaissance Teams. *Journal of Biocommunications,* 18, pp. 10-15.

Cox, D. (1992) Caricature, Readymades, and Metamorphosis: Visual Mathematics in the Context of Art. *Leonardo,* 25.3/4, pp. 295-302.

Cox, D. (1996) *Cosmic Voyage:* Scientific Visualization for IMAX Film [Abstract]. *Siggraph 96 Visual Proceedings,* 129.

Cox, D. (1998) What Can an Artist Do for Science: 'Cosmic Voyage' IMAX Film. In: Sommerer, C. and Mignonneau, L. eds. *Art @ Science.* New York, Springer Wien, pp. 53-59.

Cox, D. (2000) Creating the Cosmos: Visualization & Remote Virtual Collaboration [presentation]. Consciousness Reframed, 23-30 August 2000, University of Wales College-Newport.

Cox, D. (2000) Myth Information: Toward a Science of Consciousness [Abstract]. *Journal of Consciousness Studies.* 10-15 April 2000, University of Arizona, p. 170.

Cox, D. (2002) *Search for Life* [scientific visualization, digital-dome show]. Located at Hayden Planetarium, American Museum of Natural History.

Cox, D. (2003) *Big Bang* [scientific visualization, permanent installation]. Located at

Hayden Planetarium, American Museum of Natural History.

Cox, D. (2003) *Passport to the Universe* [scientific visualization, digital-dome show]. Located at Hayden Planetarium, American Museum of Natural History.

Cox, D. (2003) Algorithmic Art, Scientific Visualization, and Tele-Immersion: An Evolving Dialogue with the Universe. In: Malloy, J. ed. *Art, Women and Technology*. Cambridge, MA, The MIT Press, pp. 242-259.

Cox, D. (2004) The Art and Science of Visualization: Metaphorical Maps and Cultural Models. *Technoetic Arts: A Journal of Speculative Research*, 2, pp. 71-79.

Cox, D. (2004) Visualization in the Life Sciences. In: Subramaniam, S. ed. *Databasing the Brain: Data to Knowledge*. New York, Wiley Press, pp. 123-152.

Cox, D. (2006) *Black Holes: the Other Side of Infinity*. [scientific visualization, digital-dome show] Held at Denver Museum of Nature and Science Gates Planetarium.

Cox, D. (2006) Leonardo da Vinci: Man, Inventor, Genius Exhibition. Chicago Museum of Science and Industry. Chicago, IL, April-September. Modern Day Leonardo Profile Available from: <http://www.msichicago.org/scrapbook/scrapbook_exhibits/leonardo/modern/bios2/cox.html>. [Accessed 18 December 2008].

Cox, D. (2006) Metaphoric Mappings: The Art of Visualization. In: Fishwick, P. ed. *Aesthetic Computing*. Cambridge, MA, The MIT Press, pp. 89-114.

Cox, D., Kindratenko, V., and Pointer, D. (2003) IntelliBadge™: Towards Providing Location-Aware Value-Added Services at Academic Conferences. In: Dey, A., Schmidt, A., McCarthy, J. eds. *Ubiquitous Computing*, 12 October, 2003, Seattle, WA. Berlin, Springer, pp. 264-280.

Cox, D., Patterson, R. and Thiebaux, M. (2000) *Virtual Reality 3D Interface System for Data Creation, Viewing, and Editing*. USA Patent 6154723.

Crary, J. (1990) *Techniques of the Observer: On Vision and Modernity in the Nineteenth Century*. Cambridge, MA, The MIT Press.

Cruz-Neira, C., Sandin, D. and DeFanti, T. (1993) Surround-Screen Projection-Based Virtual Reality: The Design and Implementation of the CAVE. In: Cunningham, S. ed. Proceedings of the 20th Annual Conference on Computer Graphics and Interactive Techniques, September, pp. 135-142.

Czernuszenko, M., Pape, D., Sandin, D., DeFanti, T., Dawe, G., and Brown, M. (1997) The ImmersaDesk and Infinity Wall Projection-Based Virtual Reality Displays. *Computer Graphics*, 32, pp. 46-49.

Davies, S. (2008) Constructing Communication: Talking to Scientists About Talking to the Public. *Science Communication*, 29, pp. 413-434.

Davis, P. and Rabinowitz, P. (1984) *Methods of Numerical Integration.* Orlando, Academic Press.

Dawkins, R. (1976) *The Selfish Gene.* Oxford, Oxford University Press.

Dawkins, R. (1998) *Unweaving the Rainbow: Science, Delusion and the Appetite for Wonder.* Boston, Houghton Mifflin.

De Chardin, T. [1955] (1959) *The Phenomenon of Man.* Translated from the French by Rene Hague. London, William Collins Sons and Co.

DeFanti, T., Brown, M. and Stevens, R. (1996) Virtual Reality Over High Speed Networks. *IEEE Computer Graphics and Applications,* 16, pp. 42-43.

Diamond, J. [1997] (1999) *Guns, Germs, and Steel: The Fates of Human Societies.* New York, W. W. Norton and Company.

Diamond, S. (2005) Degrees of Freedom: Models of Corporate Relationships. *Leonardo,* 38, pp. 409-413.

Dodge, M. and Kitchin, R. (2001) *Atlas of Cyberspace.* Harlow, England, Addison-Wesley.

Douglas, C., Cole, M, Efendiev, Y, Ewing, R, Ginting, V, Johnson, C., Jones, G, Lazarov, R., Shannon, C., and Simpson, J. (2003) Workshop on Dynamic Data-Driven Application Systems. *Proceedings of the International Conference on Computational Science, ICCS 2003,* 2-3 June 2003, Melbourne, Australia, pp. 321-333.

Draaisma, D. (2000) *Metaphors of Memory : A History of Ideas about the Mind.* Cambridge, MA, Cambridge University Press.

Dubow, J. (2000) 'From a View on the World to a Point of View in It': Rethinking Sight, Space and the Colonial Subject. *Interventions,* 2, pp. 87-102.

Duncan, J. and Humphreys, G. (1989) Visual Search and Stimulus Similarity. *Psychological Review,* 96, pp. 433-458.

Durand, F., Drettakis, G., Thollot, J., and Puech, C. (2000) Conservative Visibility Preprocessing Using Extended Projections. *Computer Graphics and Interactive Techniques, ACM SIGGRAPH Proceedings.* July 23-28, 2000, New Orleans, LA, pp. 239-248.

Dyson, F. (1988) *Infinite in All Directions.* New York, Harper and Row.

Dyson, G. (1997) *Darwin Among the Machines: The Evolution of Global Intelligence.* Cambridge, MA, Perseus Books.

Ebert, D., Rohrer, R., Shaw, C., Kukla, J., and Roberts, D. (2000) Procedural Shape Generation for Multi-Dimensional Data Visualization. *Computers and Graphics,* 24, pp. 375-384.

Edney, M. (2007) Mapping Parts of the World. In: Akerman, J. and Karrow Jr., R. eds. *Maps: Finding Our Place in the World.* Chicago, University of Chicago Press, pp. 117-157.

Edward Said on Orientalism. (1998) Directed by Sut Jhally. [DVD: television documentary].

Elkins, J. (1999) *The Domain of Images.* Ithaca, Cornell University Press.

Ellson, R. and Cox, D. (1988) Visualization of Injection Molding. *Simulation: Journal of the Society for Computer Simulation,* 51.5, pp. 184-188.

Emmer, M. (1993) *The Visual Mind,* Cambridge, MA, The MIT Press.

Epstein, L.C. (1987) *Relativity Visualized.* San Francisco, Insight Press.

Erickson, J. (2006) Shedding Light on Black Holes. *Rocky Mountain News,* 1 February, pp. 1-2.

Fayyad, U., Grinstein, G., and Wierse, A. (2002) *Information Visualization in Data Mining and Knowledge Discovery.* San Francisco, Morgan Kaufmann.

Feekes, G. (1986) *The Hierarchy of Energy Systems, From Atom to Society.* Oxford, Pergamon Press.

Ferris, T. (1982) *Galaxies.* New York, Stewart, Tabori and Chang.

Fishwick, P. (2006) *Aesthetic Computing,* Cambridge, MA: The MIT Press.

Fishwick, P. (2008) Special Section Introduction: From the Leonardo Archive. *Leonardo,* 41, p. 390.

Fishwick, P., Diehl, S., Prophet, J., and Lowgren, J. (2005) Perspectives on Aesthetic Computing. *Leonardo,* 38, pp. 133-141.

Flagg, B. (2006) *Black Holes: the Other Side of Infinity Summative Evaluation of Planetarium Film with Students.* Report for Denver Museum of Nature and Science. Multimedia Research. Research Report 06-009.

Foley, J. and Ribarsky, B. (1994) Next-Generation Data Visualization Tools. In: Rosenblum, L., Earnshaw, R., Encarnacao, J., Hagen, H., Kaufman, A., Klimenko, S., Nielson, G., Post, F., and Thalmann, D. eds. *Scientific Visualization Advances and Challenges.* London: Academic Press, pp. 103-127

Folk, M., Pourmal, E., Schoof, L., and Miller, M. (2001) Sharable and Scalable I/O Solutions for High Performance Computing Applications [Tutorial]. Supercomputing 2001, 10-16 November, 2001, Denver, CO.

Forceville, C. (1994) Pictorial Metaphor in Advertisements. *Metaphor and Symbolic Activity,* 9, pp. 1-29.

Forceville, C. (1996) *Pictorial Metaphor in Advertising.* London: Routledge.

Foster, I. and Kesselman, C. (1999) *The Grid: Blueprint for a New Computing Infrastructure.* San Francisco, Morgan Kaufmann.

Francis, G., Goudeseune, C., Kaczmarski, H., Schaeffer, B., and Sullivan, J. (2003) ALICE on the Eightfold Way: Exploring Curved Spaces in an Enclosed Virtual Reality Theatre. In: Hege, H and Polthier, K. eds. *Visualization and Mathematics III.* New York, Springer.

Franke, H. (1987) The Expanding Medium: The Future of Computer Art. *Leonardo,* 20, 335-338.

Freidel, D., Schele, L. and Parker, J. (1993) *Maya Cosmos: Three Thousand Years on the Shaman's Path,* New York, Quill/William Morrow.

Friedhoff, R.M. and Benzon, W. (1989) *Visualization: The Second Computer Revolution,* New York, Harry N. Abrams.

Friendly, M. and Palsky, G. (2007) In. Akerman, J. and Karrow Jr., R. eds. *Maps: Finding our Place in the World,* pp. 207-253. Chicago, University of Chicago Press, pp. 65-115.

Fruhauf, T., Gobel, M., Haase, H. and Karlsson, K. (1994) Design of a Flexible Monolithic Visualization System. In: Rosenblum, L. ed. *Scientific Visualization Advances and Challenges.* London, Academic Press Limited, pp. 265-285.

Fry, B. (2007) *Visualizing Data: Exploring and Explaining Data with the Processing Environment.* Sebastopol, CA, O'Reilly Media.

Gadon, E. (1989) *The Once and Future Goddess: A Symbol for our Time.* San Francisco, HarperCollins.

Geller, M. and Huchra, J. (1989) Mapping the Universe. *Science,* 246, pp. 885, 897-904.

Gershon, N. (1994) From Perception to Visualization. In: Rosenblum, L., Earnshaw, R., Encarnacao, J., Hagen, H., Kaufman, A., Klimenko, S., Nielson, G., Post, F. and Thalmann, D. eds. *Scientific Visualization Advances and Challenges.* London, Academic Press, pp. 129-139.

Glanz, J. (1998) Cosmos in a Computer. *New York Times / Science,* 5 June, pp. 1522-1523.

Glanz, J. (2000) Halo Reveals Remains of Milky Way's Galactic Snacks. *New York Times / Science,* 11 April.

Glanz, J. (2000) Robotic Telescope Affirms Assumption on Universe's Birth. *New York Times / Science,* 7 June.

Goethe, J. [1840] (1967) *Theory of Colours.* Translated from the German by C. Eastlake. London, Frank Cass and Company.

Goldberg, K. (2001) *The Robot in the Garden: Telerobotics and Telepistemology in the Age of the Internet.* Cambridge, The MIT Press.

Gombrich, E. (1973) Illusion and Art. In: Gombrich, E. and Gregory, R. eds. *Illusion in Nature and Art.* New York, Charles Scribner's Sons, pp.193-243.

Gombrich, E., Hochberg, J., and Black, M. (1972) *Art, Perception, and Reality.* Baltimore, The Johns Hopkins University Press.

Gordin, D. and Pea, R. (1995) Prospects for Scientific Visualization as an Educational Technology. *The Journal of the Learning Sciences,* 4, pp. 249-279.

Gough, M. (2005) *The Artist as Producer: Russian Constructivism in Revolution.* Berkeley, University of California Press / Ahmanson-Murphy Fine Arts.

Grau, O. (2001) History of Telepresence: Automata, Illusion, and Rejecting the Body. In: Goldberg, K. ed. *The Robot in the Garden: Telerobotics and Telepistemology in the Age of the Internet.* Cambridge, MA, The MIT Press, pp. 226-243.

Green, K. (2000) *Passport to the Universe:* Intergalactic Travel is Still Science Fiction. *Access,* 13.1. Available from: <http://access.ncsa.uiuc.edu/Releases/02Releases/03.06.02_NCSA_and_A.html> [Accessed 18 December 2008].

Greenia, M. (2000) *History of Computing* [CD-ROM]. Second edition. Available from: Lexikon Services.

Gregory, R. (1990) *Eye and Brain. The Psychology of Seeing.* Princeton, Princeton University Press.

Gregory, R. and Gombrich, E. (1973) *Illusion in Nature and Art.* New York, Charles Scribner's Sons.

Gross M. (1994) Subspace Methods for Visualization of Multiresolution Data Sets. In: Rosenblum, L., Earnshaw, R., Encarnacao, J., Hagen, H., Kaufman, A., Klimenko, S., Nielson, G., Post, F. and Thalmann, D. eds. *Scientific Visualization: Advances and Challenges.* San Diego, Academic Press, pp. 171-186.

Haber, R. and McNabb, D. (1990) Visualization Idioms: A Conceptual Model for Scientific Visualization Systems. In: Nielson, G. and Shriver, B. eds. *Visualization in Scientific Computing.* Los Alamitos, CA, IEEE Press, pp. 74-93.

Hall, A. (1960) *The Scientific Revolution: 1500-1800--The Formation of the Modern Scientific Attitude.* Boston, Beacon Press.

Hall, M., Betts, A., Cox, D., Pointer, D., and Kindratenko, V. (2005) The Visible Radio: Process Visualization of a Software-Defined Radio. In: *VIS 05 IEEE,* Los Alamitos, CA, IEEE Press, pp. 159-165.

Hallyn, F. (2000) *Metaphor and Analogy in the Sciences,* Dordrecht, The Netherlands:

Kluwer Academic Publishers.

Harley, J. (2001) *The New Nature of Maps: Essays in the History of Cartography.* Baltimore, Johns Hopkins University Press.

Harvard Law Review (1994) Visual Artists' Rights in a Digital Age. *The Harvard Law Review Association,* 107.8, pp. 1977-1994.

Hawkes, T. (1977) *Structuralism and Semiotics.* Berkeley, University of California Press.

Hawking, S. (1988) *A Brief History of Time: From the Big Bang to Black Holes.* Toronto, Bantam Books.

Haynes, R. (1997) Dreaming the Sky: The Aborigines' View of the Cosmos is based in Their Concept of Dreaming. *Sky and Telescope,* September, pp. 72-75.

Headley, C. (1997) Platonism and Metaphor in the Texts of Mathematics: Godel and Frege on Mathematical Knowledge. *Man-and-World,* 30, pp. 453-481.

Healey, C. (1996) Choosing Effective Colors for Data Visualization. In: Yagel, R. and Nielson, G. eds. *IEEE Visualization Proceedings of the 7th Conference on Visualization '96. 28-29* October, San Francisco, CA. Los Alamitos, CA, IEEE Computer Society, pp. 263-270.

Heims, S. (1987) *John Von Neumann and Norbert Wiener: From Mathematics to the Technologies of Life and Death.* Cambridge, MA, The MIT Press.

Hesse, M. (1966) *Models and Analogies in Science.* Notre Dame, IN, University of Notre Dame Press.

Hesse, M. (1980) *Revolutions and Reconstructions in the History of Science.* Bloomington, Indiana University Press.

Hibbard, W. (1992) Display of Scientific Data Structures for Algorithm Visualization. *IEEE Visualization Proceedings of the 3rd Conference on Visualization.* Boston, IEEE Computer Society Press, pp.139-146.

Hiltz, S. and Turoff, M. (1993) *The Network Nation.* Cambridge, MA, The MIT Press.

Hinrichs, U., Schmidt, H., and Carpendale, S. (2008). EMDialogue: Bringing Information Visualization into the Museum. In: Chen, M., Hansen, C., Ma, K., North, C., and Carpendale, S. eds. *IEEE Transactions on Visualization and Computer Graphics Visualization Week Proceedings,* 14.6. Los Alamitos CA, IEEE Computer Society, pp.1181-1188.

Hofstadter, D. (1979) *Godel, Escher, Bach: An Eternal Golden Braid.* New York, Random House.

Holton, G. (1973) *Thematic Origins of Scientific Thought.* Cambridge, MA, Harvard University Press.

Hubeli, A. and Gross, M. (2001) Multiresolution Feature Extraction for Unstructured Meshes. In: *Proceedings of the Conference on Visualization '01*, 21-26 October 2001, San Diego, CA. Los Alamitos, CA, IEEE Computer Society, pp. 287-294.

Human, K. (2006) Black Holes Get Turned Inside Out: CU Astronomer's Work with Planetarium a Scientific Thrill-Ride. *The Denver Post*, 23 April.

Hunt for the Supertwister: Chasing Nature's Most Powerful Tornadoes. (2004) Boston, PBS *NOVA*, [television program].

Ihde, D. (1991) *Instrumental Realism: Interface Between the Philosophy of Science and the Philosophy of Technology*. Bloomington, Indiana University Press.

Indurkhya, B. (1992) *Metaphor and Cognition: An Interactionist Approach*. Dordrecht, The Netherlands, Kluwer Academic.

Interrante, V., with House, D. Laidlaw, D., Taylor, R., and Ware, C. (2005) Design and Evaluation in Visualization Research [panel]. In: Silva, C.; Groller, E, and Rushmeier, H. eds. *Proceedings of IEEE Visualization Conference*, October 2005, Minneapolis, MN. Los Alamitos, CA, IEEE Press, pp. 705-708.

Itten, J. and Birren, F. (1970) *The Elements of Color: A Treatise on the Color System of Johannes Itten Based on His Art of Color*, New York, Van Nostrand Reinhold Co.

Jaki, S. (1990) *Cosmos in Transition: Studies in the History of Cosmology*. Tucson, Pachart Publishing.

Jiang, T., Ribarsky, W., Wasilewski, T., Faust, N., Hannigan, B., and Parry, M. (2001) Acquisition and Display of Real-Time Atmospheric Data on Terrain. In: Ebert, D., Favre, J., and Peikert, R. eds. *Data Visualization*, pp. 15-24.

Jones, R. (1990) *Physics as Metaphor*. Minneapolis, University of Minnesota Press.

Jones, S. (2000) Towards a Philosophy of Virtual Reality: Issues Implicit in "Consciousness Reframed." *Leonardo*, 33, pp.125-132.

Jung, C. (1959) *Flying Saucers: A Modern Myth of Things Seen in the Skies*. New York, The New American Library.

Jung, C. (1968) *Psychology and Alchemy*. In: Collected Works, Vol.12. Translated from the German by G. Adler and R. Hull. London, Routledge and Kegan Paul.

Kähler, R, Cox, D., Patterson, R. Levy, S., Hege, H., and Abel, T. (2002) Rendering the First Star in the Universe - A Case Study. *Proceedings of IEEE Visualization*, IEEE Computer Society Press. Los Alamitos, CA, IEEE Press, pp. 537–540.

Kähler, R. and Hege, H. (2002) Interactive Volume Rendering of Adaptive Mesh Refinement Data. *The Visual Computer*, 18.8, pp. 481-492.

Kallick-Wakker, I. (1994) Science Icons: The Visualization of Scientific Truths. *Leonardo*, 27, pp. 309-315.

Kandinsky, W. (1977) *Concerning the Spiritual in Art.* Translated from German by M. Sadler. New York, Dover.

Kapadia, A. and Yeager, N. Performance Evaluation of HDF Version 4 Chunking Facility When Used for Subsetting Pathfinder Data. In: Rosenblum, L., Earnshaw, R., Encarnacao, J., Hagen, H., Kaufman, A., Klimenko, S., Nielson, G., Post, F. and Thalmann, D. eds. *Scientific Visualization Advances and Challenges.* San Diego, Academic Press, p. 99.

Kauffman, S. (1995) *At Home in the Universe: The Search for Laws of Complexity.* New York, Oxford University Press.

Kauffman, S. (2008) *Reinventing the Sacred: A New View of Science, Reason, and Religion.* New York, Basic Books.

Kaufmann, W. (1979) *Black Holes and Warped Spacetime.* New York, W. H. Freeman and Company.

Kaufmann, W. (1991) *Universe.* New York, W.H. Freeman and Company.

Kaufmann III, W. and Smarr, L. (1993) *Supercomputing and the Transformation of Science.* New York, Scientific American Library.

Keller, E. and Longino, H. (1997) *Feminism & Science.* Oxford, Oxford University Press.

Keller, P. and Keller, M. (1993) *Visual Cues: Practical Data Visualization.* Los, Alamitos, CA: IEEE Society Press.

Knight, D. (1996) Illustrating Chemistry. In: Baigrie, B.S. ed. *Picturing Knowledge: Historical and Philosophical Problems Concerning the Use of Art in Science.* Toronto, University of Toronto Press, pp. 135-163.

Kniss, J., Kindlmann, G., and Hansen, C. (2002) Multidimensional Transfer Functions for Interactive Volume Rendering. *IEEE Transactions on Visualization and ComputerGraphics*, 8, pp. 270-285

Knowlton, K. (1965) Computer-Produced Movies. *Science,* 150, pp. 1116-1120.

Kobbelt, L., Campagna, S., Vorsatz, J., and Seidel, H. (1998) Interactive Multi-Resolution Modeling on Arbitary Meshes. In: *Proceedings of the ACM Conference on Computer Graphics (SIGGRAPH-98),* 19-24 July 1998, Orlando, Florida. pp. 105-114.

Kruger, A. (1998) Automatic Graphical Abstraction in Intent-Based 3D-Illustrations. *Proceedings of the Working Conference on Advanced Visual Interfaces,* New York. ACM, pp. 47-56.

Krupp, E. (1991) *Beyond the Blue Horizon: Myths and Legends of the Sun, Moon, Stars, and Planets.* Oxford, Oxford University Press.

Kuhn, T. [1962] (1970) *The Structure of Scientific Revolutions.* Chicago, University of

Chicago Press.

Kurzweil, R. (2000) *The Age of Spiritual Machines: When Computers Exceed Human Intelligence.* New York, Penguin Books.

Lakoff, G. (2002) *Moral Politics: What Conservatives Know that Liberals Don't.* Chicago, The University of Chicago Press.

Lakoff, G. and Johnson, M. (1980) *Metaphors We Live By.* Chicago, The University of Chicago Press.

Lakoff, G. and Johnson, M. (1999) *Philosophy in the Flesh: The Embodied Mind and Its Challenge to Western Thought.* New York, Basic Books.

Lakoff, G. and Nunez, R. (2000) *Where Mathematics Comes From: How the Embodied Mind Brings Mathematics into Being.* New York, Basic Books.

Latour, B. (1979) Drawing Things Together. In: Latour, B. and Woolgar, S. eds. *Laboratory Life: The Social Construction of Scientific Facts.* Beverly Hills, Sage, pp. 16-98.

Latour, B. (1987) *Science in Action: How to Follow Scientists and Engineers through Society.* Cambridge, MA, Harvard University Press.

Latour, B. [2002] (2004) There is No Information, Only Transformation. In: Lovink, G. ed. *Uncanny Networks: Dialogues with the Virtual Intelligentsia,* Cambridge, MA, The MIT Press, pp. 154-160.

Latour, B. and Woolgar, S. (1979) *Laboratory Life: The Social Construction of Scientific Facts.* Beverly Hills, Sage.

Lederman, L. and Teresi, D. (1993) *The God Particle: If the Universe Is the Answer, What Is the Question?* New York, Delta.

Lehmann, K. (1945) The Dome of Heaven. *The Art Bulletin,* 27, pp. 1-27.

Leigh, J., Johnson, A., Brown, M., Sandin, D., and DeFanti, T. (1999) Visualization in Teleimmersive Environments. *IEEE Computer,* December, pp. 67-73.

Levi-Strauss, Claude (1963) *Structural Anthropology.* New York, Basic Books.

Lewin, R. (1993) Paleolithic Paint Job. *Discover the World of Science,* 14.7, pp. 65-68.

Licklider, J. [1960] (2001) Man-Computer Symbiosis. In: Packer, R. and Jordan, K. eds. *Multimedia: From Wagner to Virtual Reality.* New York, W. W. Norton & Company, pp. 55-63.

Lorensen, W. and Cline, H. (1987) Marching Cubes: A High Resolution 3D Surface Construction Algorithm. *Computer Graphics,* 21, pp. 163-169.

Lucas, T. (2004) NSF Proposal, ISE Award.

Lucas, T. (2008) [Summarizing my working relationship with you over the years]. Letter to D. Cox, 4 November.

Lynch, M. and Woolgar, S. [1988] (1990) *Representation in Scientific Practice.* Cambridge, MA, The MIT Press.

Machiraju, R., Zhifan, Z., Fry, B., and Moorhead, R. (1998) Structure-Significant Representation of Structured Datasets. *IEEE Transactions on Visualization and Computer Graphics,* 4.2, pp.117-132.

MacKinlay, J. (1986) Automating the Design of Graphical Presentations of Relational Information. *ACM Transactions on Graphics,* 5, pp. 110-141.

Malina, R. (2006) A Forty-Year Perspective on Aesthetic Computing in the *Leonardo* Journal. In: Fishwick, P. ed *Aesthetic Computing.* Cambridge, MA, The MIT Press, p. 49

Manovich, L. (2008) "Data Visualization as New Abstraction and as Anti-Sublime." In: Hawk, B., Reider, D., and Oviedo, O. *Small Tech: The Culture of Digital Tools.* Electronic Mediations Series, 22. Minneapolis, University of Minnesota Press.

Margulis, L. and Sagan, D. (1986) *Microcosmos: Four Billion Years of Microbial Evolution.* New York, Simon & Schuster.

Martin, E. (1991) The Egg and the Sperm: How Science has Constructed a Romance Based on Stereotypical Male-Female Roles. *Signs: Journal of Women in Culture and Society,* 16.3, pp. 85-97.

Maturana, H. and Varela, F. (1980) *Autopoiesis and Cognition: The Realization of the Living.* Boston, MA, D. Reidel.

Maturana, H. and Varela, F. [1987] (1992, with Afterword) *The Tree of Knowledge: The Biological Roots of Understanding,* Boston, MA, Shambala Publications, Inc.

McConville, D. (2007) Cosmological Cinema: Pedagogy, Propaganda, and Perturbation in Early Dome Theaters. *Technoetic Arts: A Journal of Speculative Research,* 5, pp. 69-85.

McCormick, B., DeFanti, T., and Brown, M. (1987) Visualization in Scientific Computing. *Computer Graphics,* 21.6.

Merleau-Ponty, M. (1962) *Phenomenology of Perception.* London, Routledge and Kegan Paul.

Merritt, R.K. (2001) From Memory Arts to the New Code Paradigm: The Artist as Engineer of Virtual Information Space and Virtual Experience. *Leonardo,* 34, pp. 403-408.

Mitchell, W. (2003) *Beyond Productivity: Information Technology, Innovation and Creativity.* Washington, DC, National Academy Press.

Mitman, G. (1993) Cinematic Nature: Hollywood Technology, Popular Culture, and the American Museum of Natural History. *The History of Society,* 84, pp. 637-661.

Mitman, G. (1993) Hollywood Technology, Popular Culture, and the American Museum of Natural History. *ISIS,* 84, pp. 637-61.

Monster of the Milky Way: A Supermassive Black Hole. (2006) Boston, PBS *NOVA,* [television program].

Morabito, M. (1986) Enter the Online World of LucasFilm. *Run,* pp. 24-28.

Morphy, H. (2001) *Aboriginal Art,* London, Phaidon Press.

Moser, S. (1996) Visual Representation in Archaeology: Depicting the Missing-Link in Human Origins. In: Baigrie, B. ed. *Picturing Knowledge: Historical and Philosophical Problems Concerning the use of Art in Science.* Toronto, University of Toronto Press, pp. 184-214.

Munzner, T., Johnson, C., Moorhead, R., Pfister, H., Rheingans, P., and Yoo, T. (2006) NIH-NSF Visualization Research Challenges Report Summary. *IEEE Computer Graphics and Applications,* 26, p. 20.

National Science Foundation. (2007) CreativeIT Program, NSF Division of Information and Intelligent Systems. Available from: <http://www.nsf.gov/pubs/2008/nsf08572/nsf08572.htm> [Accessed 18 December 2008].

NCMIR. (2003) National Center for Microscopy and Imaging Research.

NCSA. (2004) NCSA Helps NOVA "Hunt for the Supertwister" [Internet], National Center for Supercomputing Applications. Press Release, issued 23 March. Available from: <http://www.ncsa.edu/News/Access/Releases/04Releases/03.23.04_NCSA_Helps.html> [Accessed 15 November 2008].

NCSA. (2006) NCSA visualizes "Black Holes: The Other Side of Infinity" [Internet], National Center for Supercomputing Applications. Press Release, issued 1 February. Available from: <http://access.ncsa.uiuc.edu/Releases/02.01.06_NCSA_visua.html> [Accessed 15 November 2008].

NCSA. (2003) Tiled Display Wall.

NCSA. (2002) VisBench..

Neafus, D. (<dneafus@dmns.org) 8 December 2008. <top full digital domes in US> Email to D. Cox (cox@ncsa.uiuc.edu).

Nechvatal (2001) Towards an Immersive Intelligence. *Leonardo,* 34, pp. 417-422.

Nietzsche, F. (1954) On Truth and Lie in an Extra-Moral Sense. Translated from the

German by W. Kaufman. In: Kaufmann, W. ed. *The Portable Nietzsche*. Harmondsworth, Penguin, pp. 42-47.

Noll, R. (1985) Mental Imagery Cultivation as a Cultural Phenomenon: The Role of Visions in Shamanism. *Current Anthropology*, 26.4, pp. 443-461.

Norman, M. (2008) [personal communication] Letter to D. Cox, 19 December.

Norman, M., Shalf, J., Levy, S. and Daues, G. (1999) Diving Deep: Data-Management and Visualization Strategies for Adaptive Mesh Refinement. *Computing in Science and Engineering*, 1, p. 22-32.

Novacek, M. (1994) Morphological and Molecular Inroads to Phylogeny. In: Grande, L. and Rieppel, O. eds. *Interpreting the Hierarchy of Nature: From Systematic Patterns to Evolutionary Process Theories*. San Diego, Academic Press, pp. 85-131.

Nunez, R. (2000) Conceptual Metaphor and the Embodied Mind: What Makes Mathematics Possible? In: Hallyn, F. ed. *Metaphor and Analogy in the Sciences*. Dordrecht, The Netherlands, Kluwer Academic Publishers, pp. 125-145.

O'Shea, B. (2008) [personal communication] Letter to D. Cox, 5 December.

Orcutt, J. and Smarr, L. (2004) *Collaborative Research: Looking Ahead: Designing the Next Generation Cyber-infrastructure to Operate Interactive Ocean Observatories* [Internet]. NSF Award. Available from: <http://www.nsf.gov/awardsearch/showAward.do?AwardNumber=0427974> [Accessed 18 December 2008].

Oreskes, N., Shrader-Frechette, K., and Belitz, K. (1994) Verification, Validation, and Confirmation of Numerical Models in the Earth Sciences. *Science*, 263, pp. 641-646.

Ortony, A. (1993) *Metaphor and Thought*. Cambridge, England, Cambridge University Press.

Osthoff, S. (2006) Review. Embodied and Embedded Visions: The Nineteenth Annual Conference of the Society for Literature, Science, and the Arts. 10-13 November 2005, Chicago, IL. In: *Leonardo Reviews*. Available from: <http://www.leonardo.info/reviews/books.html> [Accessed 1 February 2006].

Packer, R. and Jordan, K. (2001) *Multimedia: From Wagner to Virtual Reality*. New York, W. W. Norton & Company.

Paranjape, K. (1996) *Ancient Indian Insights and Modern Science*. Pune, India, Bhandarkar Oriental Research Institute.

Pask, G. and Curran, S. (1982) *Micro Man: Computers and the Evolution of Consciousness*. New York, MacMillan.

Patrikalakis, N.M. (1991) *Scientific Visualization of Physical Phenomena*. Tokyo, Springer-Verlag.

Pausch, R., Proffitt, D., and Williams, G. (1997) Quantifying Immersion in Virtual Reality. *Computer Graphics Proceedings, Annual Conference Series*. August 3-8, Los Angeles, California, pp. 13-18.

Peltier, S., Lin, A., Lee, D., Mock, S., Lamont, S., Molina, T., Wong, M., Dai, L., Martone, M., and Ellisman, M. (2003) The Telescience Portal for Advanced Tomography Applications. In: *Parallel and Distributed Computing: Computational Grids*, 63.5, pp. 539-550.

Peterfreund, S. (1994) Scientific Models in Optics: From Metaphor to Metonymy and Back. *Journal of the History of Ideas*, 55, pp. 59-73.

Petersen, M. (2008) Tallying the World's Planetarium Attendance [Internet]. Loch Ness Productions. Available from: <http://www.lochnessproductions.com/pltref/attend.html> [Accessed 18 December 2008].

Piaget, J. (1936) *Origins of Intelligence in the Child*. London, Routledge and Kegan Paul.

Prophet, J. and d'Inverno, M. (2006) Transdisciplinary Collaboration in "Cell." In: Fishwick, P. ed. *Aesthetic Computing*. Cambridge, MA, The MIT Press, pp. 185-196.

PUBTV ONLINE (2006) *Monster of the Milkyway*. Nielson Ratings Report 3314. Metered Grids: TRAC Media Services.

Punt, M. (2000) *Early Cinema and the Technological Imaginary*. Trowbridge, England, Cromwell Press.

Rajasekar, A., Wan, M., Moore, R., Schroeder, W., Kremenek, G., Jagatheesan, A., Cowart, C., Zhu, B., Chen, S., and Olschanowsky, R. (2003) Storage Resource Broker: Managing Distributed Data in a Grid. *Computer Society of India Journal, Special Issue on SAN*, 33.4, pp. 42-54.

Reddy, M. (1993) The Conduit Metaphor: A Case of Frame Conflict in Our Language about Language. In: Ortony, A. ed. *Metaphor and Thought*. Cambridge, England, Cambridge University Press, pp. 164-201.

Reed, D. (2003) Grids, The TeraGrid, and Beyond. *IEEE Computer*, 36, pp. 62-68.

Reed, D., Bajcsy, R., Fernandez, M., Griffiths, J., Mott, R., Benioff, M., and Lazowska, E. eds. (2005) Computational Science: Ensuring America's Competitiveness. Arlington, VA: National Coordination Office for information Technology Research and Development.

Reid, E. (2000) Hierarchy and Power: Social Control in Cyberspace. In: Smith, M.A. and Kollock, P. eds. *Communities in Cyberspace*. 2nd edition. London, Routledge.

Rew, R.K. and Davis, G. (1990) NetCDF: An Interface for Scientific Data Access. *IEEE Computer Graphics and Applications,* 10, pp. 76-82.

Ribarsky, M., Ayers, E., and Mukherjea, S. (1993) *Using Glyphmaker to Create Customized Visualizations of Complex Data.* Technical Report GVU-93-25. Georgia Institute of Technology.

Richard, I.A. (1965) *The Philosophy of Rhetoric.* Oxford, Oxford University Press.

Robertson, B. (2002) Stargazing at the Hayden Planetarium, Astronomers are Using Computer Graphics to Create the Biggest Sky Show on Earth. *Computer Graphics World*, February, pp. 32-36.

Robertson, P. (1991) A Methodology for Choosing Data Representations. *IEEE Computer Graphics and Applications,* 11, pp. 56-67.

Robinson, A. (1999) *The Story of Writing.* London, Thames and Hudson.

Rogowitz, B. and Allebach, J. eds. (1993) Data Structures and Perceptual Structures. *SPIE Proceedings: Human Vision, Visual Processing and Digital Display IV*, 1913

Rogowitz, B. and Kalvin, A.(2001) The "Which Blair Project": A Quick Visual Method for Evaluating Perceptual Color Maps. *Proceedings Visualization 2001 IEEE Visualization Conference.* 21-26 October 2001, San Diego, CA. Los Alamitos, CA, IEEE Computer Society, pp. 183-190.

Rorty, R. (1979) *Philosophy and the Mirror of Nature.* Princeton, Princeton University Press.

Rorty, R. (1989) *Contingency, Irony and Solidarity.* Cambridge, England, Cambridge University Press.

Rosch, E. and Lloyd, B. (1978) *Cognition and Categorization.* New York, John Wiley & Sons.

Ruse, M. (1996) Are Pictures Really Necessary? The Case of Sewall Wright's 'Adaptive Landscapes'. In: Baigrie, B.S., (Ed.) *Picturing Knowledge: Historical and Philosophical Problems Concerning the use of Art in Science*, pp. 303-337. Toronto, University of Toronto Press

Sacks, S. (1978) *On Metaphor.* Chicago, The University of Chicago Press.

Sagan, C. (1980) *Cosmos.* New York, Wings Books.

Said, E. (1985) *Beginnings Intention & Method.* New York, Columbia University Press.

Sandin, D., DeFanti, T. and Cruz-Neira, C. (1993) A Room with a View. In: Packer, R. and Jordan, K., (Eds.) *Multimedia: From Wagner to Virtual Reality*, pp. 266-272. New York, W. W. Norton & Company
Reprint: 2001

Sandin, D., DeFanti, T., Kauffman, L. and Spielmann, Y. (2006) The Artist and the Scientific Research Environment. *Leonardo,* 39, pp. 219-221.

Sandor, E., Fron, J. (2002) Artists Team Up for the Future: Behind the Scenes of Making Art in the 21st Century, [internet], Available from: <http://www.artn.com/bibliography/003_006_artiststeamup.html> [Accessed April 2002].

Schroeder, W., Lorensen, W., Montanaro, G., and Volpe, C. (1992) Visage: An Object-Oriented Scientific Visualization System. *Visualization Proceedings of the IEEE Conference.* Los Alamitos, CA, IEEE Computer Society, pp. 219-226.

Schroeder, W., Martin, K., and Lorensen, W. (1998) *The Visualization Toolkit, An Object-Oriented Approach To 3D Graphics.* New Jersey, Prentice Hall.

Schulten, S. (2007) Mapping American History. In: Akerman, J. and Karrow Jr., R. eds. *Maps: Finding Our Place in the World.* Chicago, University of Chicago Press, pp. 159-205.

Schumaker, L. (1976) Fitting Surfaces to Scattered Data. In: Chui, C.K., Schumaker, L. and Lorentz, G. eds. *Approximate Theory II.* New York, Academic Press, pp. 203-268.

SCIRun: A Scientific Computing Problem Solving Environment. 2001.

Segal, R. (1999) *Theorizing About Myth.* Amherst, University of Massachusetts Press.

Shaffer, E. and Garland, M. (2001) Efficient Adaptive Simplification of Massive Meshes. *IEEE Conference on Visualization / SIGGRAPH.* pp. 127-142.

Shanken, E. (2005) Artists in Industry and the Academy: Collaborative Research, Interdisciplinary Scholarship and the Creation and Interpretation of Hybrid Forms. *Leonardo,* 38, pp. 415-418.

Shannon, C. and Weaver, W. (1949) *The Mathematical Theory of Communication.* Urbana-Champaign, University of Illinois Press.

Sharer, R.J. (1994) *The Ancient Maya.* Fifth edition. Stanford, Stanford University Press.

Shearman, J. (1983) The Organization of Raphael's Workshop. *Art Institute of Chicago Museum Studies,* 10, pp. 40-57.

Sherman, W. and Craig, A. (2003) *Understanding Virtual Reality: Interface, Application, and Design.* San Francisco, Morgan Kaufmann Publishers.

Silleck, Bayley bsilleck@aol. com 3 December 2008. <RE Hello IMPORTANT information>. Email to Donna J. Cox cox@ncsa. uiuc. edu. 2008.

Smarr, L. (2001) [personal communication in his office], 16 November 2001 , University of California, San Diego, CA. 1 hour-Interview.

SMARTLab Digital Media Institute [Internet]. (2008) Available from:

<http://www.smartlab.uk.com/1about/index.htm> [Accessed 18 December 2008].

Smith, C. (1978) Structural Hierarchy in Science, Art, and History. In: Wechsler, J. ed. *On Aesthetics in Science.* Cambridge, MA, The MIT Press, pp. 9-53.

Smith, C. (1981) *A Search for Structure: Selected Essays on Science, Art, and History,* Cambridge, MA, The MIT Press.

Smith, M. and Kollock, P. (1999) *Communities in Cyberspace.* Second edition. London, Routledge.

Snyder, A. and Vesna, V. (1998) Education Automation on Spaceship Earth: Buckminster Fuller's Vision--More Relevant than Ever, *Leonardo,* 31.4, pp. 289-292.

Stafford, B. (1996) *Good Looking: Essays on the Virtue of Images.* Cambridge, MA, the MIT Press.

Stafford, B. (1999) *Visual Analogy: Consciousness as the Art of Connecting.* Cambridge, MA, The MIT Press.

Stafford, B. (2007) *Echo Objects: The Cognitive Works of Images.* Chicago, IL, University of Chicago Press.

Stepan, N.L. (1986) Race and Gender: The Role of Analogy in Science. *ISIS,* 77, pp. 261-277.

Stephenson, B. (2005) Adler Planetarium [Internet]. In: *Encyclopedia of Chicago.* Available from: <http://www.encyclopedia.chicagohistory.org/pages/23.html> [Accessed 18 December 2008].

Story of Computer Graphics, The. (1999) Produced by C. Machover. Premier Held at: SIGGRAPH, 8 August. [documentary film]

Sullivan, W. (1979) *Black Holes: The Edge of Space, The End of Time.* New York, Anchor/Doubleday.

Sumners, C., Reiff, P. and Weber, W. (2008) Learning in an Immersive Digital Theater. *Advances in Space Research,* 42, pp. 1848-1854.

Swimme, B. and Berry, T. (1992) *The Universe Story: From the Primordial Flaring Forth to the Ecozoic Era--A Celebration of the Unfolding of the Cosmos.* New York, Harper Collins.

Thiebaux, M. (1997) *Virtual Director: Steering Scientific Visualization with Virtual Camera Choreography.* MSci. Thesis, University of Illinois at Chicago.

Thompson, W. (1989) *Imaginary Landscape: Making Worlds of Myth and Science.* New York, St. Martin's Press.

Topper, D. (1996) Towards an Epistemology of Scientific Illustration. In: Baigrie, B. ed. *Picturing Knowledge: Historical and Philosophical Problems Concerning the use*

of Art in Science. Toronto, University of Toronto Press, pp. 215-249.

Tracy, S. (2007) Visualizing the Universe: Hayden Planetarium Achieves High-Quality Visualization with Commodity Hardware [Internet], Scientific Computing. Available from: <http://www.scientificcomputing.com/visualizing-the-universe.aspx> [Accessed 12 September 2007].

Tufte, E. [1983] (1985) *The Visual Display of Quantitative Information*. Cheshire, CT, Graphics Press.

Tufte, E. (1990) *Envisioning Information*. Cheshire, CT, Graphics Press.

Tukey, J. (1962) The Future of Data Analysis. *Annals of Mathematical Statistics*, 33, pp. 1-67, 81.

Unfolding Universe. (2003) Discovery Communications, Inc., 3 June, [television program].

USC Institute for Creative Technologies [Internet]. Available from: <http://ict.usc.edu/about> [Accessed 15 July 2008].

Van Bendegam, J.P. (2000) Analogy and Metaphor as Essential Tools for the Working Mathematician. In: Hallyn, F. ed. *Metaphor and Analogy in the Sciences*. Dordrecht, The Netherlands, Kluwer Academic Publishers, pp. 105-123.

Van Walsum, T., Post, F.H., Silver, D., and Post, F.J. (1996) Feature Extraction and Iconic Visualization. *IEEE Transactions on Visualization and Computer Graphics*, 2.2, pp. 111-119.

Varela, F., Thompson, E., and Rosch, E. [1991] (1997) *The Embodied Mind: Cognitive Science and Human Experience*. Cambridge, MA, The MIT Press.

Varnedoe, K. and Gopnik, A. (1990) *High & Low: Modern Art and Popular Culture*. New York, The Museum of Modern Art.

Vasarely, V. [1959-1961] (1973) *Supernovae*. Paris 1973, SPADEM.

Vasarley, V. (1966) *Vonal*. Paris, SPADEM.

Virtual World, Part 2. (2002) London, BBC, 26 March, [television program].

Von Foerster, H. (1989) The Need of Perception for the Perception of Needs. *Leonardo*, 22, pp. 223-226.

Waldrop, M.M. (1992) *Complexity: The Emerging Science at the Edge of Order and Chaos*. New York, Simon and Schuster.

Walker, H. (2005) [personal communication after art panel], SIGGRAPH, 31 July-4 August 2005, Los Angeles, CA.

Walter, J. and Healey, C. (2001) Attribute Preserving Dataset Simplification. *IEEE*

Conference on Visualization / SIGGRAPH, pp. 113-120.

Ware, C. and Beatty, J. (1988) Using Color Dimensions to Display Data Dimensions. *Human Factors*, 20, pp. 127-142.

Ware, C. (2000) *Information Visualization: Perception for Design*. New York, Academic Press.

Ware, C. (2008) *Visual Thinking for Design*. San Francisco, Morgan Kaufman/Elsevier.

Wechsler, J. (1978) *On Aesthetics in Science*. Cambridge, MA, The MIT Press.

Westermann, R. and Ertl, T. (1998) Efficiently Using Graphics Hardware in Volume Rendering Applications. *Computer Graphics Proceedings*, July 19-24, 1998, Orlando, FL. ACM SIGGRAPH, pp. 169-177.

Whitehead, A. and Russell, B. (1910-1913) *Principia Mathematica*. Cambridge, England, Cambridge University Press.

Whittock, T. (1990) *Metaphor and Film*. Cambridge, England, Cambridge University Press.

Whorf, B.L. (1956) *Language, Thought and Reality: Selected Writings*. Cambridge, MA, The MIT Press.

Whyte, L.L. [1951] (1966) *Aspects of Form: A Symposium on Form in Nature and Art*. London, Percy Lund Humphries & Co.

Whyte, L.L., Wilson, A. and Wilson, D. (1969) *Hierarchical Structures*. New York, American Elsevier.

Wiener, N. [1954] (2001) "Cybernetics in History": The Human Use of Human Beings. In: Packer, R. and Jordan, K. eds. *Multimedia: From Wagner to Virtual Reality*. New York, W. W. Norton & Company, pp. 47-54.

Wilhelmson, R. (1988) *High-Speed Computing: Scientific Applications and Algorithm Design*. Urbana-Champaign, University of Illinois Press.

Williams, D. (2007) *Monster of the Milky Way* Summative Evaluation. Report for Thomas Lucas Productions. Knight-Williams, September.

Wilson, S. (2002) *Information Arts: Intersections of Art, Science, and Technology*. Cambridge, MA, The MIT Press.

Winckler, M. and Van Helden, A. (1992) Representing the Heavens: Galileo and Visual Astronomy. *Isis*, 83, pp.195-217.

Wittgenstein, L. (1953) *Philosophical Investigations*. Oxford, Blackwell.

Woolman, M. (2002) *Digital Information Graphics*. New York, Watson-Guptill.

Wright, R. (1990) Computer Graphics as Allegorical Knowledge: Electronic Imagery in the Sciences. *Leonardo Digital Image--Digital Cinema Supplemental Issue*, pp. 65-73.

Wulf, W. (1989). The National Collaboratory. In: *Towards a National Collaboratory.* [unpublished report] NSF Invitational Workshop, March 1989, Rockefeller University, New York.

Wulf, W. (1993) National Collaboratories: Applying Information Technology for Scientific Research. National Research Council. Washington, D.C., National Academy Press.

Yeh, P., Xia-Serafino, W., Miles, L., Kobler, B., and Menasce, D. (2002) Implementation of CCSDS Lossless Data Compression in HDF. Earth Science Technology Conference, 11-13 June 2002, Pasadena, California.

Yu, K., Brownell, M., Schoemer, J., Neafus, D., Lucas, T., and Zager, Z. (2007) Lights! Cameras! Render to the Dome! Live Action Film Footage for an Astronomy Fulldome Show. In: Anonymous ed. *Planetarian: Journal of the International Planetarium Society*, pp. 6-93.

Zangwill, O. ed. (1987) *The Oxford Companion to the Mind.* New York, Oxford University Press.

Zyda, M., Cox, D., Katz, W., Larson-Mogal, J., Louie, G., Lypaczewski, P., Pausch, R., Singer, A., and Weisman, J. (1997) *Modeling and Simulation: Linking Entertainment and Defense.* Washington D.C., National Academy Press.