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CASE STUDY

New Ways of Looking and Learning in Natural History Museums: The Use of Gigapixel Imaging to Bring Science and Publics Together

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Abstract This article describes a series of demonstration projects that use multiscalar gigapixel image technology to iteratively design, test, and study how visitors learn to observe more scientifically in museums, online, and through museum-based programming. We consider how the particular affordances of systems like these can move science communication and learning from didactic approaches centered on one-way communication toward technology platforms that encourage shared observation, dialogue, and engagement.

INTRODUCTION

Natural history museums are nineteenth-century inventions facing twenty-first-century challenges. To build audiences and remain relevant, these museums must learn to engage diverse publics in ways that make real science and real objects meaningful to a variety of interests and affinities (Falk et al. 2006). Yet the desire to innovate and transform is often in tension with legacy missions of stewardship, conservation, and curating. An effective museum must also serve as a locus of engagement, involving the public directly in aspects of authentic scientific practice. While some museum sectors have made significant strides in understanding how to interactively engage the public, comparatively little has changed in natural history museums to enable publics to observe, share, speculate, and make meaning from collections and the objects they contain. Natural history museum curators and scientists—for all their deep knowledge, fascinating insights, and infectious passion for subject matter—engage the public in limited ways with muted success. Like their collections, many still remain isolated from the publics served by their museums.

Natural history museums are facing these challenges at a time when our ideas about science communication and learning are undergoing a rapid transformation (Holliman et al. 2009; Bell et al. 2009, Davidson and Goldberg 2010). Powerful information communication technologies are at hand. We co-exist with social and pervasive media. Our knowledge of effective interactive and participatory design strategies that support visitor learning continues to improve. Yet natural history museums, by and large, have been hesitant to take advantage of the logic of networked digital media platforms to transform museums into active centers for learning and engagement.

We argue that finding engaging ways for visitors to observe with the eyes of science is a promising strategy for natural history museums. This approach entails developing engagement

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Photo 1. The large composite gigapixel image of Shuwaymis West, an ancient petroglyph site in Saudi Arabia used in the *Stories in the Rock* demonstration project. *Gigapan Image courtesy of Richard T. Bryant. Copyright the Layan Cultural Foundation, Riyadh.*

strategies and internal cultures that embrace communicating with the public in contemporary ways that privilege agency, participation, dialogue, and exchange. To address this, we describe an ongoing collaboration between the Carnegie Museum of Natural History, CREATE Lab at Carnegie Mellon University's Robotics Institute, and University of Pittsburgh Center for Learning in Out-of-School Environments (UPCLOSE) to find powerful new ways to scaffold observation and dialogue around visual evidence. We are exploring the use of novel image-based visual environments to create observational experiences that support science communication and learning.

This project is a true partnership between three institutions that bring complementary skills, resources, and interests to the table. The Carnegie Museum of Natural History, one of the oldest and largest natural history museums in the United States, houses world-class collections of dinosaurs, fossils, insects, and botanical specimens, and cares for some 22 million objects. It runs an active science research program with 25 full-time scientists on staff, and reaches 500,000 visitors annually through exhibits and programming; it connects with even more online. Our technology partner, the CREATE Lab at Carnegie Mellon University's Robotics Institute, is a research group focused on technology innovation for community empowerment and learning. The lab has been at the forefront of bringing hardware and software for gigapixel imaging applications to the hands of everyday users, with educational installations in 28 countries to date (see http://education.gigapan.org/). The University of Pittsburgh Center for Learning in Out-of-School Environments is leading the learning research and design elements of this program. The center brings a multi-disciplinary group of learning scientists and design researchers together with partners to conceptualize, develop, design, and study how people learn in everyday settings.

SCAFFOLDING SCIENTIFIC OBSERVATION

Even in a highly technological age, observation remains a fundamental practice of science, especially in fields where deep looking is a core means of finding questions, generating data, and constructing evidence (Wilson 2006). Scientific observation is a highly refined and practiced form of attention that requires particular ways of coordinating the mind and the eye. It draws on distinct forms of reasoning and relies on specialized tools and systematic techniques of description and representation in order to build accepted bodies of evidence (Norris 1985). It is also a highly social practice, requiring organized communities of inquirers collaborating through time and space. The term *observation* itself has faceted meanings. Observation can mean visual perception, an empirical form of evidence, a technique with specific ways of recording and representing insights, or a community practice endowed with particular conventions and standards. Each of these facets of scientific observation represents an aspect of learning to see with a trained eye.

Observation is also a fundamental and deeply human practice. Picking out notable features for comparison and contrast and interpreting those insights is an everyday event. In *Histories of Scientific Observation*, a collection of essays that exposes the changing nature and meaning of observation, Lorraine Daston remarks that "Observation has always been a form of knowledge that straddles the boundary between art and science, high and low science, elite and popular practice" (2011). Observation bridges everyday and scientific ways of knowing and seeing and thus provides a gateway into learning. A natural history museum—like an astronomical observatory, botanical garden, or aquarium—is in essence a specialized site for observation.

Given the foundational nature of observation, how might a museum authentically teach visitors to observe with the eyes of science? Museums with their unique objects and collections have the potential to be sites *par excellence* for learning to observe, for looking closely, systematically noticing, comparing and contrasting, while trying out different forms of reasoning about what is seen. But engaging and supporting powerful forms of visual observation is tricky, with a potentially steep learning curve that makes success in an unmediated context challenging (Eberbach and Crowley 2009; Phipps and Rowe 2010). Enabling everyday observers to move toward seeing (and coming to know) with the eyes of science requires explicit educational scaffolding and mediation (Eberbach and Crowley 2012).

GIGAPIXEL IMAGING TECHNOLOGY: BIG IMAGES FOR SCIENCE, COMMUNICATION AND LEARNING

The phrase "networked, gigapixel imaging" refers to an emerging class of information communication technology that allows anyone to create massive high-resolution images, and provides an innovative platform on which to explore, discover, share, and discuss visual evidence. These multi-scale image environments allow users to seamlessly move from full views to extreme close-ups that reveal details hidden in layers of resolution that often exceed one billion pixels. This deep zoom capability works not only for familiar online mapping and satellite data applications, but any kind of high-resolution image. Image sources might be photographic (micro, macro, or panoramic) or computationally generated data visualizations and simulations played over time. These explorable big images offer new kinds of visual information spaces that are inherently social and participatory.

At the forefront of this gigapixel imaging revolution is GigaPan, an outgrowth of the PanCam technology that NASA deployed on the Mars Exploration Rover mission to acquire and view extremely high-resolution images of the Martian surface. With research support from NASA and Google, our project partners at Carnegie Mellon University's Robotics Institute have developed high-resolution into an accessible and affordable consumer technology (see www.gigapan.org). The GigaPan system consists of a robotic camera mount with a standard digital camera set up to automatically take hundreds of photographs at maximum zoom level. The photographs are then aligned, blended, and stitched to create a very large, highly detailed composite image or panorama. These gigapixel resolution images can then be uploaded to online image storage, and displayed by Web-based viewers and services that syndicate dynamic views of the resulting explorable images as social media across the Internet.

In many fields of science, observation (and the evidence it yields) is still a core method of knowledge production. Disciplines such as geology, archeology, paleontology, anthropology, entomology—as well as areas of applied research such as environmental monitoring, ecosystem management, urban planning, forensics, and infrastructure analysis—find this new gigapixel imaging technology to be particularly compelling (Sargent and Nourbakhsh 2010). Photography itself has a long and productive history of illustrating science. The accepted neutrality of the mechanical lens is a trusted ally in observation, experimentation, and archiving (Wilder 2009). Networked gigapixel images continue this history by enabling researchers to record *in situ* field and site work, and to document objects, specimens, and phenomena in unprecedented detail. The evidentiary images scientists collect may picture remote or inaccessible sites of extreme beauty, or note the state and progress of an archeological dig as the context of discovery is destroyed through the excavation process, or provide stunning macroscopic views of artifact and insect specimens for reference. These gigapixel images document both context and detail with such fidelity that they can used back in the lab for continued observation, identification, comparison, measurement, description, contextual analysis, and can serve as a nexus for scholarly debate over interpretation.

Gigapixel imagery has clearly proven itself to be a useful tool for science (Frankle 2010). Could explorable high-resolution image environments be a powerful educational and social media platform? "Deep zooming" applications are not only visually compelling, but they offer a spatial way to display and navigate through large amounts of information in a single interface using touch or gesture-based scroll, pan, and zoom controls (Bederson 2011). Text, images, graphics, audio, and video can be embedded at different zoom levels within an image, creating localized sites for commenting and conversation. We think that gigapixel image technology—and related zoomable user interfaces (ZUIs)—has six promising affordances to support engagement and learning in museum settings and online:

1). It privileges scientific observation. Dynamically stepping through increasing image magnification reveals all kinds of interesting detail not initially apparent, encouraging deep looking and noticing in a shared observational space. Users can move seamlessly between parts and the whole without losing perspective, detail, or context, as would be the case in more static displays.

2). It democratizes a tool of science. Because gigapixel images can be created and viewed easily though commercially available technologies, the platform changes the dynamics of who can make, interact with, and participate directly with scientific evidence in the form of visual data. Experts are no longer the only ones who can collect, interpret, and share high-quality images that have direct relevance to authentic science.

3). It encourages participatory learning. A networked visual image platform opens up new possibilities for engaging with science topics and new opportunities for social learning though crowdsourcing data and observations, dialogues about evidence and interpretation, and directly interacting with scientists in a joint media space. Gigapixel resolution image environments have the potential to be a social media platform that supports co-learning with original scientific data.

4). It offers alternative ways to curate content. Information in a multiscalar image can be ordered by visual-spatial logic and then combined with more traditional linear, categorical, or hierarchical ways to structure interpretation. Space as well as time becomes a moving element visitors can explore.

5). It enables context-dependent narrative. These systems can reveal contextually relevant information based on user interactions and location in the three dimensional image space (Luan et al. 2008). People are becoming familiar with these deep zoom or zoomable user interface (ZUI) experiences through mapping programs and earth browsers such as Bing Maps and Google Earth which deliver location-based information dependent on an individual user's personal explorations through a geo-spatial environment .

Finally, interactive imagery raises questions about whether we can leverage user interactions—how users scan, zoom, and linger in images, as a proxy for gaze, gesture, and, by extension, interest—to reveal content in ways that are more responsive and meaningful to individual participants. To support evaluation efforts, our system analytics collect user session and activity data which reveal where and for how long a user explores an image—providing us with fine-grained data about the path of observation.

CONTEMPORARY APPROACHES TO PUBLIC-SCIENCE ENGAGEMENT

Traditionally, science communication has been portrayed as a knowledge transmission problem. In a transmission, or "deficit," model, the public is positioned as fundamentally lacking a necessary understanding of a science topic or issue; therefore a communication *from* scientists *to* a public audience is required to increase scientific literacy (Irwin and Wynne 1996). Thus framed, science communication becomes a mechanistic act of simplifying and translating information that the expert community decides it is important for the public know. It is a one-way delivery of information controlled by experts. The knowledge transmission model works best for definitions of scientific literacy that focus on what can be gained through the delivery and receipt of information via passive modes of reading, watching, and listening, and does not take into account the role of motivation, interest, and agency in learning. This paradigmatic model continues to permeate scientific bodies and funding agencies (Palmer and Schibeci 2012, 6).

In contrast, a "dialogue" approach to science communication requires opportunities for both publics and scientists to meaningfully exchange information, perspectives, and ideas in response to a science-related issue (Bucchi 2008). This approach values the mutual learning that can occur for all involved—scientists and publics alike. Taking into account beliefs, values, local knowledge, and lay expertise, it stresses the ideals of democratic participation and the co-generation of knowledge, either through more direct involvement in the science research enterprise itself, or in support of a more engaged citizenry that can deliberate on issues of the day that involve science (Nisbet and Scheufele 2009).

Drawing on various typologies that have emerged in the science communication field, our project is guided by three frameworks that characterize interactions between science and the public: Public Understanding of Science, Public Participation in Scientific Research, and Public Engagement in Science (McCallie et al. 2009). It is worth noting that an underlying dimension in each of these frameworks is the role of agency and the degree to which a public-and-science interaction moves from information transmission to an exchange that values dialogue, participation, and mutual learning.

The Public Understanding of Science framework focuses on a more engaged version of the deficit or knowledge transmission model. This type of programming includes familiar delivery-oriented science communication efforts such as traditional object-based exhibits and displays, films and documentaries, books, and museum lectures that aim to transmit expert knowledge and tell stories. But this category also includes more reflexive modes of communication that account for activities and experiences designed to enable learners to shape their own inquiry and construct personalized knowledge. Rather than viewing the individual learner as an empty vessel to be filled with appropriate scientific knowledge, these engagement strategies support learners in actively constructing meaning and understanding as they encounter scientific messages. In museum settings, these designs take the form of interactive exhibits, participatory and hands-on activities. The sociocultural construction of knowledge happens when visitors go beyond factual knowledge and develop skills, practices, reasoning, and deeper disciplinary understanding (Bell et al. 2009). Often tied to a deficit model of communication, the Public Understanding of Science approaches have been much maligned over the years (Trench and Bucchi 2010). However, lost in this critique is the need to remember that understanding and building an operating body of knowledge is an essential feature of becoming an engaged learner.

Public Participation in Scientific Research—often called "citizen science"—is an umbrella term for research programs that strive to genuinely engage participants in the scientific process. The publics' involvement in the research program can range from contributory, to increasingly more collaborative and co-authored forms (Bonney et al. 2009). Participation can mean contributing data, and perhaps partnering on the research design or interpretation of the data. In its ideal form, the public is authentically involved in all phases of a research program, from question identification, through data collection, analysis, interpretation, and dissemination.

Public Engagement in Science is characterized by public forums and events in which scientists, stakeholders, and publics share multiple perspectives, exchange facts and opinions, and engage complex or controversial science and technology issues of public or local concern (such as predator drone use, hydrologic fracturing, climate change, vaccines, GMOs, geo-engineering). Ideally, this diverse group co-generates new knowledge that informs personal, community, and policy-level decision-making. Examples of these kinds of forums include science cafés, dialogue and deliberative events, festivals, community consultations, and public hearings. Civic participation is often the goal of these endeavors, with individual and collective decision-making and action the intended outcome. Learning institutions such as museums, universities, and libraries have the opportunity, space, and public trust to broker these types of democratic engagement and learning forums. Natural history museums as such could have important roles in all three forms of public-science engagement.

DEMONSTRATION PROJECTS

We now describe a set of design research projects that demonstrate applications of gigapixel image technology in natural history museums to the three approaches to science communication outlined above. To explore the Public Understanding of Science framework, we focus on two case studies designed to scaffold observation and find meaningful ways to share disciplinary knowledge with the public—whether that knowledge emerges from new research findings or is found in object-based collections. For Public Participation in Scientific Research, we are tackling a particular data collection challenge common to citizen-science projects: accurate and reliable species identification. To study Public Engagement in Science, we are examining the role of evidentiary images and data overlays in supporting perspective sharing and knowledge building when science is contested and central to personal and collective decision-making in a community. As we write this article, our first demonstration project is nearing completion, so we describe it in most detail. The other three projects underway are works in progress, and will be described more briefly.

For the design research phase of all four projects, we draw upon both human computer interaction and learning science research methods to ground our work. We use contextual inquiry methods to inventory the workspaces of the museum scientists—noting tools, materials, books, and so on (Holtzblatt et al. 2004). We conduct think-aloud studies to document scientists' observational practices (Qin and Simon 1990; Redish and Wixon 2002). And we use surveys and semi-structured interviews to understand their beliefs about engaging visitors in their research area. To inform our design process, we begin with a series of front-end user studies to map the kinds of prior knowledge, interest, and questions that visitors bring to the experience (Martin and Hanington 2012). Throughout the prototyping process, we use a variety of methods to improve the usability and user experience, and to study how and to what extent the experiences support observational practices.

Demonstration Project 1: Stories in the Rock

The Carnegie Museum of Natural History, like many science institutions, is interested in finding ways to share its scientists' research findings with public audiences. In this demonstration project, the team is using gigapixel image technology to increase the museum's capacity to quickly, easily, and effectively communicate cutting-edge scientific discoveries—and the visual evidence for them—to museum visitors and Web audiences.

Sandra Olsen, archeologist and the museum's head of Anthropology, leads a team of researchers investigating a set of extremely well preserved petroglyph sites found in remote areas of the Saudi Arabian desert. Etched into large rock faces are dynamic scenes of prehistoric people hunting wild animals, herding cattle, riding camels, and engaging in warfare on horseback. Some of these ancient rock art engravings date back to the Holocene Wet Phase (8,000 BCE–3,500 BCE), when the environment in the Arabian Peninsula was more savannah-like. The petroglyphs provide unmistakable evidence of lions, cheetahs, hyenas, gazelles, ibexes, and extinct wild cattle roaming the land. Scenes from later periods show the domestication of animals

Photos 2a-2c. Petroglyph details from Photo 1 taken from the multitouch user interface developed for the *Stories in the Rock* demonstration project, viewed at increasing degrees of magnification, focusing on the curled horns of an auroch.

for food, herding, transport, as well as signs of increasing tribal warfare as the climate became more arid. To document these remarkable petroglyph sites for research and communication purposes, Olsen's research team is using several imaging techniques, including GigaPan photography, to capture ancient works of art in unprecedented detail.

The first example of interactive gigapixel technology being used to share Olsen's Saudi petroglyph research involved collaboration between our Pittsburgh-based team and the British Museum for their 2012 Diamond Jubilee exhibition, *The Horse: From Saudi Arabia to Ascot*, which traced the influence of horses in Middle Eastern history from their domestication around 3,500 BCE to the present day. Several of the Saudi petroglyph sites reveal distinct evidence of early equid domestication and breeding practices relevant to the exhibition. To share this evidence and its interpretation with visitors, the museum installed a high-definition projector with an accompanying touch screen kiosk that allowed visitors to select a gigapixel image of six petroglyph sites for closer examination. A deep zoom would carry visitors from a panoramic vista of rocky outcrops in the Saudi desert to captioned close-up views of individual rock carvings showing battle scenes with lance-carrying warriors, wheeled chariots, and Arabian horses with tribal markings and tack—all visible with enough clarity to see the maker's tool marks.

From a curatorial perspective, gigapixel image technology allowed a narrative leap that would have been difficult using traditional artifacts and media. This was only the second time that the British Museum had allowed interactive screen-based media exhibits into its object-centric galleries. In interviews exhibition developers mentioned that digital media tends to be used only when it advances an exhibit theme or objective in some critical way that real objects cannot. In this case, the high-resolution photographs of the Saudi petroglyphs enabled curators to bring in new research evidence and ideas regarding the evolutionary and cultural roots of the horse. Moreover, the large desert landscapes projected on the gallery wall gave an immediate sense of space and place to the story of the Arabian horse.

Despite the incorporation of cutting-edge media technology, the British Museum installation took a fairly traditional exhibit design approach—distilling curator interpretation and insights into fixed text labels and screen captions to convey explanatory information about an object, artifact, specimen, or site that fits into a larger exhibition narrative. Beyond the selection of a petroglyph site to view, the exhibition was not responsive to a visitor's particular interests, or open to self-directed exploration of the image. Nor was the exhibit designed to support disciplinary ways of observing, comparing, and contrasting in a methodical way. The installation did not fully exploit the technology to coordinate close looking, noticing, and learning to observe with the lens of an archeologist where features are not cognitive endpoints, but clues for reasoning. While remaining true to a Public Understanding of Science mode of engagement that emphasizes knowledge building, we wished to explore deeper levels of interaction, responsive to visitors' interests and agency.

We have since begun developing *Stories in the Rock*, a demonstration project using the same Saudi petroglyph sites, to experiment with how gigapixel image technology can be designed to support more engaged forms of observation and learning based on user interactions and interest. In particular our goals for this project are:

1). To coordinate looking and reasoning about observed features with the eyes of science.

2). To share curatorial interpretation and content based on visitors' interest-driven explorations and interactions with the subject matter.

To achieve these goals we leveraged the resolution afforded by these big images in two ways—as a large-scale physical print medium, and as an interactive digital media platform. First, to create a pop-up exhibition space for prototyping the demonstration project, we printed a high-quality 4-foot-by-10-foot panoramic photograph of one of the Saudi petroglyph sites (see photo 1). This large image acts both as eye-catching backdrop, and as a narrative element. Associated with the panoramic print are three poster-sized images—snapshots pulled from zoomed-in sections within the print—which show in remarkable detail carved scenes of early human activity and culture. Each of these close-up images of a rock art panel is paired with an audio story—for example, an imagined narrative told from a child's point of view that shares the excitement of a young boy planning his first hunt as he points out the different hunting strategies pictured in the rock.

The second exhibition element is an interactive gigapixel image viewer that uses visitor-driven exploration and interactions within the space to tailor the content experience to a user's interest. The exhibit uses an economical 24-inch multitouch screen setup with seating to accommodate three viewers comfortably and encourage longer exploration times. A start screen introduces *Stories in the Rock* and invites users to touch the screen. The interface allows the multiscale image to be freely explored through simple drag-to-pan/tilt, pinch-to-zoom multitouch gestures. It also offers browsing by a curator-selected set of topics tied to individual "interest spots" located at different resolution levels within the image.

Tapping on an interest spot opens up an overlay window with additional multimedia mediation (image, text, audio, video, graphics, animation) to support visitor observations and learning. For example, if a user selects the topic of "hunting scenes," several "interest spots" are highlighted within the image. Tapping one of these spots zooms users into a close-up view of a leopard figure with its distinctive stalking pose and long curled tail clearly outlined. To the right an overlay box displays text and the photograph of a present day leopard in a similar pose, making it much easier for a first time observer to discern the somewhat ambiguous animal form engraved in the rock. Visitors can return to a full view, or pan and zoom to another interest spot nearby and see a video of a curator explaining how an engraving of an auroch, a now extinct form of wild cattle, as been covered by later petroglyph artists. These changing layers of animal assemblages are indicators of an increasingly arid environment, revealing a story of climate change and the desertification of the Arabian Peninsula. Throughout the image, interest spots have been located in x-y-z space and carefully paired with text, audio-visual media, and graphics selected to enable learners to notice, make connections, establish comparisons, and thereby move from perceptual to more conceptual and explanatory forms of reasoning about what they perceive.

One focus of this demonstration is to find time and cost-effective ways to extend the curator's voice and observations in ways that are iterative, personal, and collaborative. A well-composed gigapixel image taken in the field or in the lab doubles both as a form of scientific evidence collected for research purposes, and as an artifact around which to organize exhibition elements on the floor and online. This saves time, since it enables the curator to use research images for exhibits, public programming, and public relations, without additional work or expense in the field.

Secondly, since this demonstration was deliberately framed as an experimental effort, it allowed the museum to take a more inventive, iterative, and rapid approach to the exhibit development process. All elements in the exhibit—the digital media user interface, the interpretive text, the overlay media, and the big print display system—are intentionally designed to be easily modified, updated, and replaced. Multiscalar image platforms offer a very large interpretive space with new narrative and non-narrative possibilities. Freed from a strict organizational or thematic structure, the curator was able to experiment with different types of annotations—amusing details from the expedition experience, video clips of her Saudi collaborators, and imagined backstories based on the evidence, which reveal cultural and human connections. These annotations, or content overlays, which appear as the visitor is examining the petroglyphs, offer many possibilities for rich mediation. Our next step is testing out which mediation strategies best encourage engagement and observational practices that coordinate disciplinary ways of looking and thinking.

Demonstration Project 2: The Big Bone Room

Natural history museums exist in large part because of their collections. From their inception, object-based museums have faced the challenge of how to involve the public in understanding and valuing carefully selected, preserved, documented, and stored specimens than can number in the tens of millions. Typically, this communication challenge has been resolved through exhibits with text, educator-led tours, and lectures, with their inherent tendency toward one-way communication. Moreover, these strategies access only a tiny fraction of the total collection.

To overcome the limitations of traditional displays in terms of access and interpretation, institutions have been taking innovative steps to expose more of their collections. For example, the recently opened Visible Storage Study Center at the Brooklyn Museum's Luce Center for American Art takes an open storage, open access approach by creating a working museum storeroom for over 2,000 objects, open to both the public and professionals. On view are rolling racks of hundreds of paintings from the permanent collection and tightly packed vitrines of significant objects labeled and stored in climate-controlled conditions. Taking another tack, the Virtual Museum of Canada features 600 virtual exhibits and over a million images, which enable the online public to view collections from museums across the country. The Darwin Center at the Natural History Museum in London turns the museum inside out with a striking new building designed to showcase collections in floors of open storage which stun the eye with the sheer number, variety, and kaleidoscopic beauty of specimens lifted from the natural world. The museum's research spaces are also purposefully designed to connect scientists working at lab benches with the public through conversation and demonstration.

Each of these approaches tackles the challenge of increasing public access to objects in storage, and providing interpretation. But each of these *viewing* efforts still functions at the edges of *observation*. While these efforts help visitors understand something about the objects in a collection, there is still a gap between looking at the objects as a visitor and appreciating them as a scientist.

Gigapixel image environments provide a technologically mediated way to manage access and interpretation of collections that privilege close observation. Carnegie Museum of Natural History holds one of the best collections of Jurassic-age dinosaur fossils in the world, including the holotype, or name-bearing specimens of *Diplodocus carnegii* and *Tyrannosaurus*

Photos 3a-3c. Mayfly specimen taken with a Gigamacro rig. *Gigapixel image courtesy of Gene Cooper, Four Chambers Studio and Stephanie Sanner, Powdermill Nature Reserve.* 3b-c. Right: Detail views from Photo 3 showing mouthpart structures and tarsal leg claw features that aid taxonomic identification activities.

rex on display (Gangewere 2001, 193). Stored away from view in the ground floors of the museum are equally important collections of fossils. The large fossil vertebrate collection, or "Big Bone Room" as it is affectionately known to museum staff, is one of the most popular behind-the-scenes tour stops. The fossil bones are big, real, rare, and, for the most part, isolated from public view.

Each dinosaur fossil carries with it a unique and often fascinating history—an expeditionary story of discovery, moments of scientific intrigue, recognizable details of structure and function—that sheds light on the morphology and behavior of these remarkable creatures that once roamed the Earth and the scientists who study them. Museum paleontologist Matthew Lamanna wants to share—and visually explain—what he sees in these fossilized bones. Using only a standard digital camera on a GigaPan rig, the team easily created a high-resolution image of part of the Big Bone Room to begin prototyping the user interface and mediation elements. The curator then uses a freely available online service to locate and mark up points of interest in the image.

Visitors will be able to access these stories via rich media overlays including historical photos, artist's reconstructions of dinosaurs, video clips with scientists at dig sites and in the lab, 3D animations of CAT scan data and so forth. We will install the multitouch gigapixel viewer in the museum's public dinosaur exhibition space so that visitors can explore the Big Bone Room beneath their feet while visiting the museum and online. In addition to making available this rich trove of fossils and media that the museum has amassed over more than a century, we are also seeking ways to support dialogue and interactions between the public and the research staff. Future iterations of this use case will test ways to connect with the public beyond the walls of the museum through virtual tours, asynchronous conversations, and mediated online exchanges between and with scientists.

Demonstration Project 3: Overcoming the taxonomic bottleneck: Training for expert observation

In certain areas of science, knowledge generation requires a large dataset collected from diverse, dispersed locations over time. Such large-scale research projects can benefit from the involvement of the public in data collection, documentation, geo-location, and identification activities (Bonney et al. 2009). One ongoing challenge for such data-intensive projects is providing resources, training, and interactions with specialists so that diverse individuals can participate meaningfully as citizen scientists (Hochachka et al. 2012). A particular hurdle

that limits public participation in environmental biomonitoring activities is the “taxonomic bottleneck,” which occurs when a research protocol requires non-specialists to provide accurate and reliable species identification beyond what is reasonably possible given the tools and training commonly available (Conrad and Hilchey 2011).

Museum ecologists and entomologists currently lead several regional freshwater stream-monitoring programs for the Commonwealth of Pennsylvania. They also help watershed and conservancy groups in their efforts to establish reliable baseline data on stream conditions for water quality monitoring and management activities. Our Public Participation in Scientific Research demonstration project employs networked gigapixel image technology to unlock the expertise and collections at Powdermill Nature Reserve—the museum’s offsite research station—to better support regionally focused environmental biomonitoring research with citizen groups and science professionals.

One of the most effective practices for measuring water quality and stream health over time is to monitor underwater insect populations and record change. Insects collected in streams are increasingly used as indicators of ecosystem conditions because aquatic arthropods provide an extremely sensitive, integrated reading on water quality, unlike chemical and physical data that only provide a snapshot of a stream’s parameters at the exact time of the collection. Effective biomonitoring requires regular sampling of set locations, ideally over the full geographic extent of a watershed. Productively involving volunteers in site sampling and species identification tasks increases the range and capacity of these research programs to broadly monitor conditions. Furthermore, it can be a first step in building the community relationships needed to support deeper forms of engagement in the science research and communication processes.

Stream biomonitoring begins with a relatively straightforward sampling procedure. It requires participants trained in an accepted data collection protocol to take to the field on a seasonal basis with waders, a kick-net, Ziploc bags, and a notebook in hand. To collect a sample, a riffle section of streambed is “kicked up” to dislodge and capture the benthic macroinvertebrates living there. Next the participants must sort, identify, and count the number of underwater insect types found in each sample. With relatively little training, most students and volunteers can classify aquatic insects (mayflies, stoneflies, caddisflies, and so on). However, reliably identifying an unknown organism down to sub-order or family, as desired scientifically, is challenging, and can even be difficult for lab-certified technicians.

In interviews, museum researchers and educators described frustrations with the existing training materials and reference tools available for learning to classify aquatic macroinvertebrates. The so-called identification bible, *The North American Guide to Aquatic Insects,* is an expensive and comprehensive tome based on a complex dichotomous key structure. It uses specialized descriptive language that, for non-expert users, invariably leaves room for errors and wrong turns at the many branch points. Scaled-down guides and keys tailored to specific regions and for educational purposes may include color photographs or drawings with enlargements of one or two key characteristics. Often these distinguishing characters and diagnostic features are shown in simplified monochrome line or shaded stipple drawings. Other materials such as flashcards, identification tables, and images of varying quality are also available online. For its classification activities, the museum has the gold standard—a labeled set of "voucher specimens" preserved in alcohol vials for reference. But all these static aids can be difficult to interpret for students and participants in training, especially given individual variability in the size, color, and form of field-collected specimens found at different locations and lifecycle stages.

To examine whether an explorable image platform can help address the taxonomic identification bottleneck endemic in many citizen science projects, we are working with museum researchers and staff to create an online "digital teaching collection." Our project seeks to supplement the existing visual materials and identification keys with dynamic, high-resolution macrophotographs of voucher specimens from the museum's collection. Together with Four Chamber Studios, we have prototyped a low cost macrogigapixel image capture rig specialized for museum use (http://gigamacro.com). In addition to the image capture technology, we are developing a multiscalar comparative viewer that enables dynamic side-by-side comparison, so that two unknown specimens can be ganged together and observed at increasing levels of magnification to examine key features that would differentiate, for example, a damselfly from a dragonfly larvae. In addition, multimedia annotations—supporting text, illustrations, range maps, seasonal photographs—tied to zoom level—are overlaid to help the classifier recognize the subtle distinctions in morphology, color, and size that are necessary to differentiate between families of organisms within a taxonomic system. To support species identification we are developing measuring and drawing tools for noting size and adding graphic pointers to mark features, as well as functionality to allow conversation and commenting about what is seen.

In this demonstration project we are studying the affordances of a multiscalar image platform to enhance observational practices particular to a domain of science, in this case taxonomic identification. We guide observational activities with media-rich annotations revealed in the context of visual inquiry, while preserving the visual relationships between parts and wholes, and by enabling people to easily cross-reference key physical characteristics necessary to identify unknown organisms. With this robust observational system in place, our next task is developing the communication tools to enable communities of observers—in our case, partners and museum research staff—to use an explorable image platform to coordinate observations and data, organize collective inquiry, and motivate individual user participation in a shared environmental research endeavor.

Demonstration Project 4: Images as evidence: Scientific data and public debate

Natural gas drilling in the recently tapped Marcellus and Utica shale formations presents a major economic development opportunity for Pennsylvania. A game-changing technological advance—the combination of horizontal drilling with slick water hydraulic fracturing—is unlocking a vast new reserve of energy for development in our region. At the same time, these resource extraction activities, and the development of the processing and transmission infrastructure for this shale gas boom, pose significant environment- and health-related questions for the region. Community members are looking for places to engage in informed, meaningful learning and discussion.

Marcellus shale gas development challenges citizens, landowners, communities, businesses, as well as environmental, educational, and civic leadership, to understand and make difficult choices in view of competing concerns—water use and disposal, air quality, infrastructure development and maintenance, land management, economic growth, and myriad community impacts. Supporting the best possible science-informed decision-making in this complex ecology requires collective knowledge-building, advanced dialogue, and data sharing between a diverse set of stakeholders.

We are exploring how gigapixel-image-based cyberinfrastructure (timemachine.gigapan.org) can support the integration and co-location of visual evidence in the form of geolocated, high resolution landscape documentation over time, and in combination with LandSat (http://earthengine.google.org/#intro) and other public data sources to deepen science-rich dialogue, envisioning, and decision-making processes.

We are developing the gigapixel platform to promote community engagement, deliberation, and creative solution finding for this natural resource development issue. It will serve as:

1). A *dialogue event tool* for presentation, elicitation, and recording by participants to: a) present panoramic images in public forum and panel discussions, b) print visually impressive, panoramic images for public viewing, discussion, and facilitation; c) record post-event discussions within the Web-based image to support context-specific dialogue which persists over time.

2). An *online environment* for the integration of multiple data sources that enable stakeholders and publics to interact around the visual evidence, by depicting and annotating drill sites over time, revealing the process of development, operation, and mitigation; describing what the community values; and revealing personal identity, connection, and local knowledge of the land, its places, and people.

3). A high-resolution panoramic photography tool for *geolocated visual documentation* to support monitoring of best practices descriptions, and sharing by developers, communities, and other stakeholders.

Museums want to be locations for and organizations that inform civic debate involving science and technology. But museums themselves can be caught in the crosshairs of the debate. The Carnegie Museum of Natural History wants to support the establishment of science-based best practices, bio-monitoring activities, and environmental impact research, but it also holds a sizeable tract of land in its nature reserve that could be leased for drilling-related activities and could bring much needed revenue into the organization. Like the region, the museum itself is conflicted and facing complex decisions which science alone cannot answer.

REFLECTIONS AND FUTURE DIRECTIONS

We have provided several examples of how a new interactive visual platform is being positioned to help transform natural history museum experiences. Visual evidence is put at the heart of the dialogue, creating experiences that encourage public interactions with science through viewing, interpreting, collecting, and debating observations and interpretations via an explorable, multiscalar image environment

Technologies that reveal the unseen and exploit novel and spectacular optical experiences have always been the underlying power in "devices of wonder." Barbara Stafford and Frances Terpak document the trajectory of this singular feature of visual experience over time in their exhibition *Devices of Wonder: From the World in a Box to Images on Screen*, at the J. Paul Getty Museum (Stafford and Terpak 2001). From miniature dioramas, panoramic rotundas, magic lanterns, holograms, and stroboscopes, to IMAX domes—these liminal visual experiences offer moments for renewed wonder and, with them, chances for visitors to form new connections and construct new meanings. Museums must continue to explore and exploit the potential for optical technologies, serving as devices of wonder, to attract and amaze visitors.

Gigapixel image technology enables more than just new kinds of interactivity in museums, exemplified by input interfaces such as multi-touch tablets, iPads, or gesture-based inputs with Kinect-like controllers. Our work concentrates—not only on the interface—but also on the deep connections scientists make between data, observation, and scientific interpretation. Truly explorable images easily surface those connections and open the museum's scientific resources, expertise, and content to the world. We see gigapixel images as boundary objects that tie together the scientific and public sides of the house through a shared observational space (Fischer 2010) .

Explorable visual environments will proliferate as technology advances. These kinds of revealing technologies will have profound implications for institutions like natural history museums that are in essence specialized sites for collective observation. These institutions are now exploring new approaches to science communication that stress engagement, exchange, and agency on the part of learners. They are racing to take advantage of the social and participatory dimensions of our networked world. Museums have spent years accumulating the collections and expertise that are at the heart of some of the most urgent scientific questions of the day. Shareable, zoomable, networked high-resolution images offer novel opportunities to connect museums with the public and provide museums with a new, relevant, and consequential role in advancing science and society. END

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