Computer Graphics and Cultural Heritage

From One-Way Inspiration to Symbiosis, Part 1

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For almost 50 years, cultural heritage in its many guises has been inspiring computer scientists with computational challenges rooted in the evidence of past human experience. In the early experiments, computer scientists did little more than point the way to future applications. This served as inspiration to ’60s researchers to provide solutions that avoided the limits of the technologies of the day. In those days, “results” would be recognizable to cultural-heritage professionals more from the way they showed computer scientists dabbling in cultural heritage than from any proven ability of computer science to offer practical solutions.

Of course, from the graphics perspective, publications at the time, such as those by George Cowgill (who reported archaeological applications as far back as 1958)[1] and others at the 1967 Fall Joint Computer Conference,[2,3] had few images. That research predated the availability of color raster devices by perhaps five years, with the graphics being mainly vector displays or “green on green” on the then state-of-the-art Tektronix storage tube. Vector-based color displays such as the Evans & Sutherland devices used in early flight simulators existed but were expensive and were the fairly exclusive preserve of well-capitalized industrial applications.

Now, information and communications technology (ICT) tools and techniques are being debated seriously as offering the prospect of making the world’s cultural heritage accessible online through digitization. *The New Renaissance*,[4] a 2011 report commissioned by the European Commission, justified the estimated 100-billion-euro cost of digitization to bring “our complete heritage online” as follows: “Digitisation breathes new life into material from the past, and turns it into a formidable asset for the individual user and an important building block of the digital economy.” The report defined heritage for these purposes as the contents of museums, libraries, and archives, “such as sculptures, paintings, music and literature.” Although the report’s arguments on the cost and feasibility of such a vision can be questioned, there’s no doubting its seriousness and ambition.

The first part of this article shows how computer graphics, computational geometry, and interactive techniques have contributed to the development of tools and applications for documenting and preserving tangible cultural heritage. In the second part, I’ll demonstrate how the trust and techniques developed in these areas are empowering computer scientists and cultural professionals to collaborate on developing tools and techniques that couldn’t have been envisaged before the advent of computing.

My examples progressively develop from dealing with relative certainty (documenting tangible objects) to the informed inference in activities such as reconstruction and visualization. As the next section shows, even for physical artifacts, our knowledge is a delicate combination of physical evidence and significance, both of which are part of documenting the heritage. So, outside this article’s scope are developments in other computing-science areas such as artificial intelligence, knowledge engineering, and natural-language processing. These areas are also enriching the data and its uses, but in more ambiguous and interpreted areas—for example, the representation of uncertainty and the narratives that give an object its significance.

What Makes Cultural Heritage Different and Challenging?

Setting the context for early experiments in technological support for cultural-heritage professionals might seem irrelevant to current computer

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science graduates, who might argue that ’60s technologies have nothing to inform current challenges. That would miss the point. Although current technologies’ capabilities and capacity dwarf the “programmable calculators” of the ’60s, many challenges that cultural-heritage professionals now face would be eminently recognizable to their ’60s counterparts. In fact, it seems that computer science has taken almost 50 years to begin to offer tools and solutions that integrate fully with the workflows and challenges facing cultural-heritage professionals ranging from museum curators to archaeologists and archivists, conservators, and restorers and historians.

Why are these challenges so daunting even for the most advanced technologies? What characteristics of the cultural-heritage field make it so difficult for computing tools to provide effective solutions? The answers seem to lie in an apparent lack of appreciation in computing circles of the combination of extremely challenging data, potentially in vast quantities, and the sensitive and at times uncertain nature of what that data represents.

Culture has these two related definitions: “the arts and other manifestations of human intellectual achievement regarded collectively” and “the ideas, customs, and social behaviour of a particular people or society.”[5]

Here’s how UNESCO describes “World Heritage”:[6] “Heritage is our legacy from the past, what we live with today, and what we pass on to future generations. Our cultural and natural heritage are both irreplaceable sources of life and inspiration. … World Heritage sites belong to all the peoples of the world, irrespective of the territory on which they are located.” Elsewhere, UNESCO defines cultural heritage in various ways, such as “tangible” and “intangible,” including describing it as a means for communities to create and value their cultural identities and as a resource to underpin economic regeneration.

Cultural heritage has much in common with education and health. We all have our own heritage in the same way we’ve all acquired learning and a state of health, and it’s a unique combination of an inheritance from our past and the results of life’s journey. This individualized, very personal association with cultural heritage has led some to define it as the significance of the tangible evidence of the past in the present. This definition as *significance in the present* has also led some to point out that cultural heritage can be manufactured—with the significance embodied and created primarily through the narratives surrounding the tangible evidence. Our heritage, defined this way, is unique to each of the planet’s seven-billion-plus people—a living, reinterpreted, and changing inheritance to which we all bring different perspectives.

Figure 1. The Cambodian temple Ta Prohm, also called the “Angelina Jolie Temple.” You could argue that the temple’s use as a location for the movie *Lara Croft: Tomb Raider* fundamentally changed its significance.

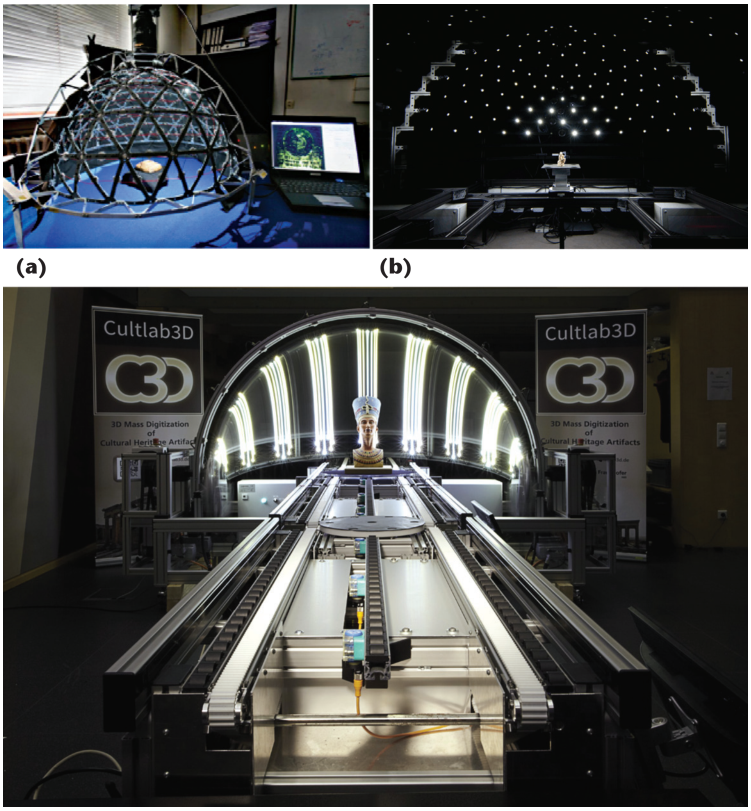
Consider the Bamiyan Buddhas, two gigantic statues carved in the cliffs of the Bamiyan valley in Afghanistan. They had served for centuries as a site of religious significance and more recently as a tourist destination. In 2001, the Taliban destroyed them, declaring them idolatrous and an insult to Islam. After their demolition, they acquired different meaning.

A perhaps less obvious example is the Cambodian temple Ta Prohm (see Figure 1), which at least some local inhabitants now call the “Angelina Jolie Temple.” You could argue that its use as a location for the movie *Lara Croft: Tomb Raider* fundamentally changed its significance.

These cases differ in not only how much the evidence of the past has changed but also how their significance now differs among individuals. This significance could draw on a combination of the physical evidence, the intermediate events, and the narratives presented by thought leaders, whether inspired by religious belief, media reporting, politics, or entertainment. For computer graphicists, the message is clear. Every time we create a visualization or interpretation of a cultural object or site, we’re potentially adding to its cultural significance. We should seek to do that in an informed way.

Recording Tangible Evidence

The most basic functionality with which technology can assist cultural-heritage professionals is in documenting surviving artifacts. But even here, there



(a) (b) (c)

Figure 2. Three devices for documenting optically complicated objects. (a) The Catholic University of Leuven's MiniDome employs controlled lighting in single-camera image-based capture. (b) The University of Bonn's moveable Multiview Dome employs a combination of structured-light and image-based recording technologies. (c) The new CultLab3D Scanner from the Fraunhofer Institute for Computer Graphics Research won the DigitalHeritageExpo's prize for technical proficiency. (Figure 2c courtesy of the Fraunhofer Institute for Computer Graphics Research.)

are challenges of size, detail, and material that have been addressed only gradually over time, and significant challenges remain unmet. Early projects tended to just capture and structure metadata about cultural objects, rather than capture representations of the objects themselves. Next came systems in which images represented cultural objects.

For many people, the serious documentation of tangible cultural-heritage objects became a real possibility with the development of 3D laser scanning in the 1990s,[7] alongside imaging methods for recording cultural artifacts.[8] These technologies' deployment was dramatically demonstrated in the Digital Michelangelo project[9] and in the range of high-profile projects capturing archaeological sites and architectural heritage that Lon Addison described.[10] Possibly the most impressive project he described was the time-of-flight laser scanning of Tambo Colorado in Peru, which captured 30 million points with an accuracy of 2 mm.

In 2004, Michelangelo's *David* was cleaned and restored. At that time, scientists also examined small fractures that had been visible on the statue's lower legs since it was moved to the Galleria dell'Accademia in Florence in 1873. A time series of repeated 3D measurements highlighted the potential of monitoring the fractures to determine whether they were growing.[11] (This example, along with some I mention later, formed part of the Reshaping History: A Future for Our Past exhibition.[12] Content from that exhibition has toured at several European venues since 2012 and will be shown in Brazil in August and September 2014.)

In parallel, image-based techniques were developing rapidly, including photogrammetry and structure-from-motion computer vision techniques,[8,13] which capture 3D by moving a handheld video camera around an object. The documentation of optically complicated objects remains challenging.[14] Researchers have designed and built many devices targeting different types of objects and operating conditions. These devices have employed tailored recording technologies using

- triangulation of structured light;
- time-of-flight laser scanning;
- controlled lighting in single-camera image-based capture—for example, the Catholic University of Leuven's MiniDome[15] (see Figures 2a and 3a through 3d); and
- combinations of technologies—for example, the University of Bonn's Multiview Dome[16] (see Figures 2b and 3e).

The most recent entry has been Fraunhofer's CultLab3D scanner at the Institute for Computer Graphics at Darmstadt (see Figure 2c).[17] Unveiled at the Digital Heritage International Congress 2013 in Marseilles, it won the DigitalHeritage-Expo's prize for technical proficiency.

At the same time, researchers were developing systems that computed depth maps from a set of uncalibrated images. For example, the ARC3D (ARC stands for Automatic Reconstruction Cloud) system,[18,19] also from the Catholic University of Leuven, went live with a free service to the public in 2005 and was more recently integrated with MeshLab.[20] This system and more recent ones (such as Autodesk 123D Catch) could enable wider public engagement in documenting cultural heritage and its significance to various communities through Web-based resources.

Interpreting the Evidence to Reconstruct the Past

Cultural-heritage artifacts are rarely pristine. Usually, excavation at archaeological sites produces a

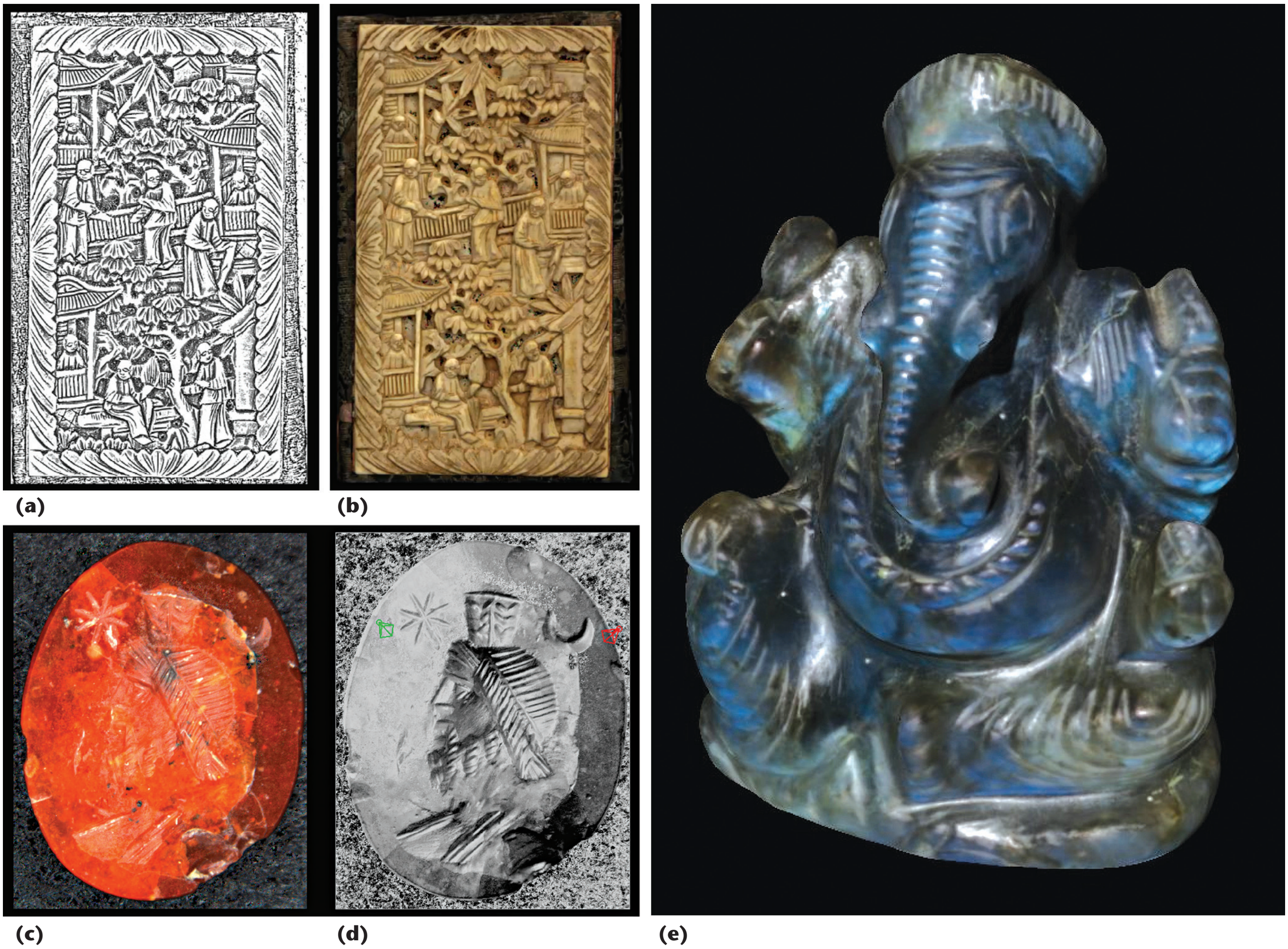


Figure 3. Results with the MiniDome and Multiview Dome. (a) An ivory panel captured using the MiniDome and rendered with the "line drawing" rendering mode. (b) The rendered panel, with color texture added. (c) A conventional photograph of a carved intaglio of Serapis. (d) A monochrome 3D model of the intaglio created with the MiniDome, showing details of the carving. (e) A labradorite Ganesh digitized using the Multiview Dome. (Figures 3c and 3d © Katholieke Universiteit Leuven and 3D-COFORM; used with permission.)

series of fragments that the archaeologist might want to consider as potentially from a single original artifact. For example, Figure 4 shows a small fraction of the thousands of stone fragments recovered from the Egyptian archaeological site of the temples at Karnak.

Even if all the pieces survive, the combinatorics of pairwise comparison of such large collections would make exhaustive search an impractical approach to matching pieces. This is particularly true bearing in mind that it was common to reuse stones from one monument in new ones, reversing the stones and carving new designs on the exposed sides. In addition, missing pieces between the surviving fragments make alignments more difficult to determine and might make physical reassembly impossible. Even when a sufficient amount of the original survives, weight or fragility might make physical handling impractical or unwise from a curatorial viewpoint, risking additional damage. Here, I review case studies that demonstrate challenges computer scientists face in these circumstances, the approaches they've taken, and enhanced documentation's potential benefits.

Fragment Reassembly

A common challenge for archaeologists is that many excavated finds are recovered in pieces following their burial under later depositions. Such finds are rarely complete, and individual fragments might be worn.

For example, David Koller and his colleagues reported on recreating the *Forma Urbis Romae*, a map of Ancient Rome carved in marble and measuring approximately 18 × 13 m. The map previously was on a wall of the Templum Pacis.[21] The 1,186 extant pieces are now separated from the original building and exhibit various degrees of wear and tear. However, despite their size and weight, they've been digitized in 3D. Koller and his colleagues

Figure 4. Stone fragments from the archaeological excavation of the temples at Karnak, Egypt. Even if all the pieces survive, the combinatorics of pairwise comparison of such large collections would make exhaustive search an impractical approach to matching pieces.

used a variety of properties and characteristics of the remaining fragments to detect alignments and edge matches, by

- searching for fragments of similar thickness;
- matching features of the carving at edges (for example, where the line of a road, carved on the marble's surface, reaches the edge of one fragment and would have aligned with a matching feature on a neighboring fragment);
- matching the edge fracture geometry; and
- multivariate clustering, in which new pairings or groupings of fragments share common characteristics including "fragment thickness, marble veining direction, axial direction of the incised architecture, presence and orientation of slab edges, and the back surface condition of the fragments (rough, smooth, or unpreserved)."[22]

Of course, damage might occur more violently through human-caused or natural incidents. An example of the first case was the Bamiyan Buddhas I mentioned earlier. After their destruction, there were proposals to rebuild them from the shattered pieces.[23] Also, researchers have constructed virtual environments based on a range of photographs, from newly taken images of the empty niches to documentation photos and tourist photos from the 1970s.[24,25] However, discussion continues about whether reconstruction is appropriate and how to represent the narrative of their destruction.[26]

In 2009, an earthquake in Abruzzo in central Italy severely damaged the *Madonna di Pietranico*, a beautiful devotional statue. Curators recovered many terra-cotta fragments, but some parts were missing, and those that remained were fragile. Reconstructing it by manual experiment would have been difficult and would have risked further damage. In addition, the reconstructed statue required internal support that had to take into account the missing pieces.

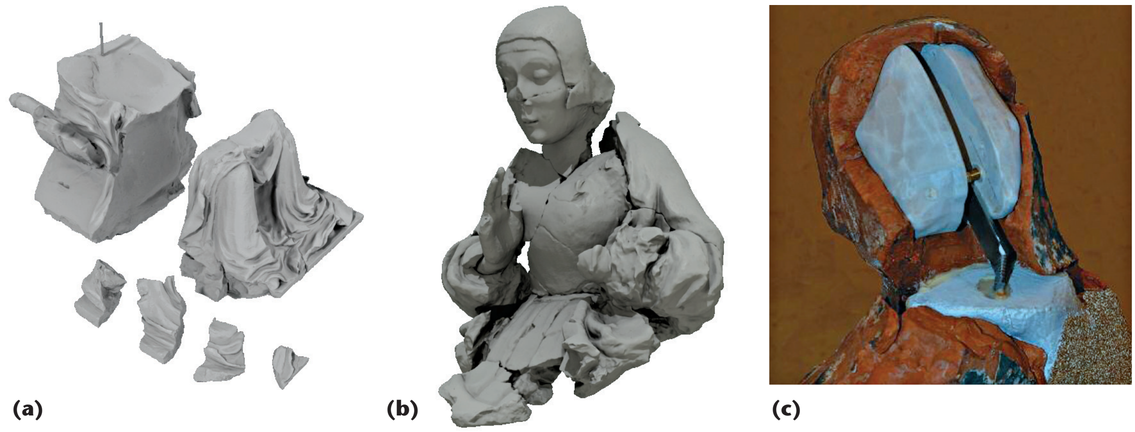
The solution was a close partnership of traditional methods and 3D technology.[27] Conservators matched fragment pairs by eye; these were then scanned and modeled. They planned the reconstruction virtually to piece together the statue. By working in 3D, they could test the fit of the fragments before physically reassembling the statue. The finished 3D model's surfaces were used to construct new internal supports that fit exactly and that were essential to support the Madonna in her attitude of prayer (see Figure 5).

The final step restored color to the statue. Because significant damage had occurred to the original layers of color, conservators used the 3D model to test ideas. With the colors agreed upon and applied, the restoration was complete.

Drawing on Secondary Sources

Laocoon and His Sons is a monumental ancient marble sculpture initially discovered in pieces in Rome in 1506; further fragments were discovered in the 20th century. Its reconstruction has been controversial, with different configurations proposed over many years.

By digitizing the fragments accurately in 3D, researchers can evaluate hypothetical reconstructions. However, the statue is geometrically complex, with occlusions and restricted access to portions of the surface. Polished marble also isn't the easiest surface to capture with structured-light scanners. So, Bernd Breuckmann and his colleagues scanned 20th-century plaster copies of the parts.[28] These plaster copies could be physically separated into sections, allowing better access, and the plaster was easier to scan than the polished marble.



(a) (b) (c)

Figure 5. The restoration of the *Madonna di Pietranico.* (a) Digital models of the major pieces of the statue's plinth. (b) The recovered pieces of the statue's upper part, virtually reassembled. (c). A rear view of the Madonna's head showing the tailored supports fitted inside the statue. The finished 3D model's surfaces were used to construct internal supports that fit exactly and support the Madonna in her attitude of prayer. (Images © CNR-ISTI and 3D-COFORM; used with permission.)

Plaster casts, many made in the 19th century, become cultural objects in their own right as well as being secondary documentation, in the same way that written texts can help understand historic objects. As I'll show in part two of this article, secondary documentation is particularly valuable when the objects themselves are lost or damaged. This data offers new opportunities by providing some evidence over time, which must be interpreted to take into account manufacturing processes. In the future, it might enable restorations to reverse damage such as that caused by pollution-fuelled acid rain.

A Meissen porcelain table fountain at the Victoria and Albert Museum (V&A) was made in many pieces around 1775 as a copy of an architectural fountain in Dresden. It has never been reassembled. The challenge has been to discover how the pieces fit together. Many of the pieces are large, unwieldy, and fragile. There's no handbook showing how to assemble the table fountain, so trial and error are necessary, particularly because some pieces are missing. Fortunately, the original fountain is still on the grounds of a palace in Dresden, which gives another source of evidence for the composition of the statue parts and for the nature of the missing pieces.

Researchers have progressively digitized the pieces of the V&A's copy in 3D and have tested an application that helps curators explore ways to reassemble the fragments (see Figure 6).[27] Because this is a virtual reconstruction, the missing pieces don't pose a challenge to structural integrity, and the 3D models let curators explore strategies for supporting the existing pieces. The researchers have also used the PhotoCloud display tool[29] to show the relationship between the 3D models, the original Dresden fountain, and historical records (see Figure 7). Work continues at the V&A to complete reconstruction of the table fountain and develop an exhibit to open later in 2014.[30]

These examples demonstrate how 3D technologies can complement and assist traditional restoration techniques, improving both the practicality of the processes and, potentially, the restoration's quality.

Helping Determine Provenance

Scientists have long used chemistry to establish provenance and deduce the significance and narratives behind the tangible. For example, David Nash and his colleagues investigated variations in the chemical composition of prehistoric silcrete tools to help establish relationships between places in sub-Saharan Africa.[31] In recent years, DNA has provided a unique signature to establish provenance and to make connections. For example, to establish identity, researchers compared the DNA of European royal families to remains believed to be of the family of the last Czar, Nicholas II.[32] Computer scientists are beginning to similarly use the documentation they collect.

Each of the following three examples used the underlying shapes of objects digitized in 3D to investigate their provenance. This doesn't provide proof of a particular provenance but can provide evidence to help cultural-heritage professionals reach their judgments. Such judgments are always based on a range of evidence, and computer graphics and computational geometry are increasingly providing an additional perspective.

Michelangelo and the Palestrina Pietà

The *Palestrina Pietà* is a marble sculpture that has been attributed to Michelangelo, but no written

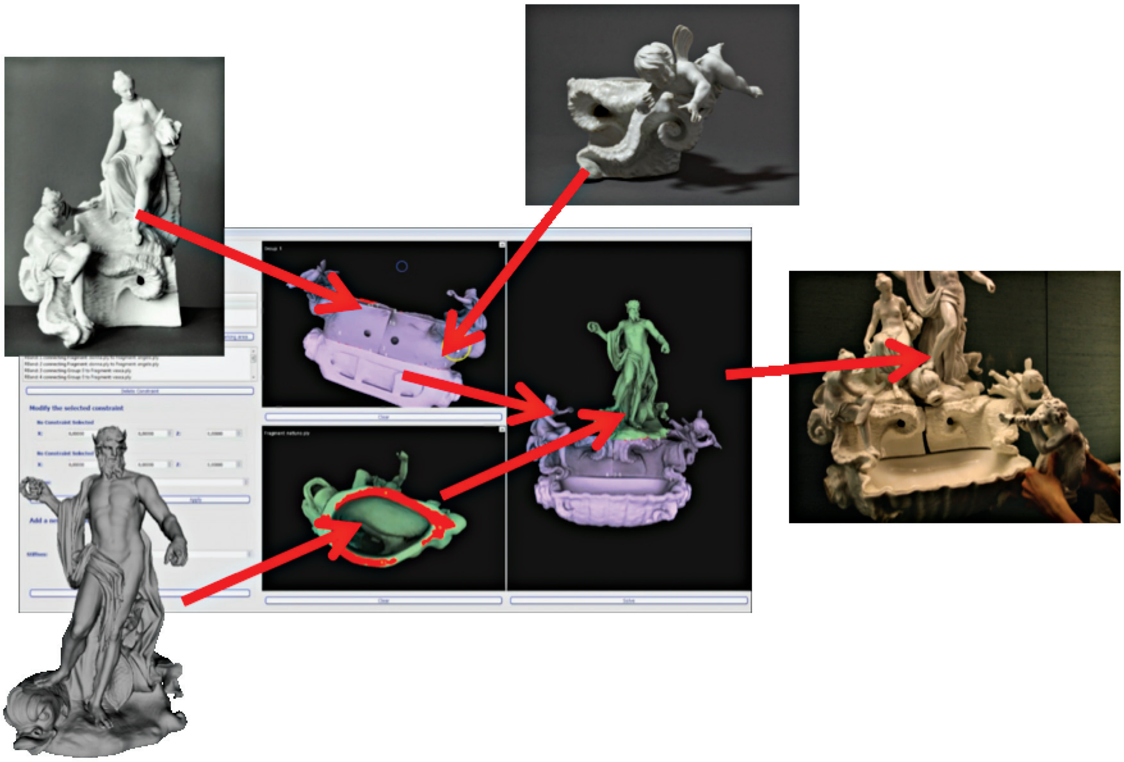


Figure 6. Reassembling a Meissen table fountain. The pieces were digitized in 3D; curators used the virtual pieces with a fragment reassembler application to plan the alignment and assembly without handling the fragile pieces. (Images © Victoria and Albert Museum, London)

Figure 7. Navigating a collection of 306 photos of Meissen table fountain pieces using the PhotoCloud browser. The images, some of the digitized Meissen table fountain pieces, and some historic engravings are all registered onto a 3D scan of the original Dresden architectural fountain. Each data source presents additional information to inform the other representations. (Images © CNR-ISTI and 3D-COFORM; used with permission.)

evidence exists to prove the attribution. A collaborative team used 3D technology to study chisel marks on the sculpture.[33] Comparing the marks with those found on works known to be Michelangelo's, the team sought to determine whether Michelangelo created the statue.

This research also stimulated a broader debate. The challenging and, for many people, unexpected

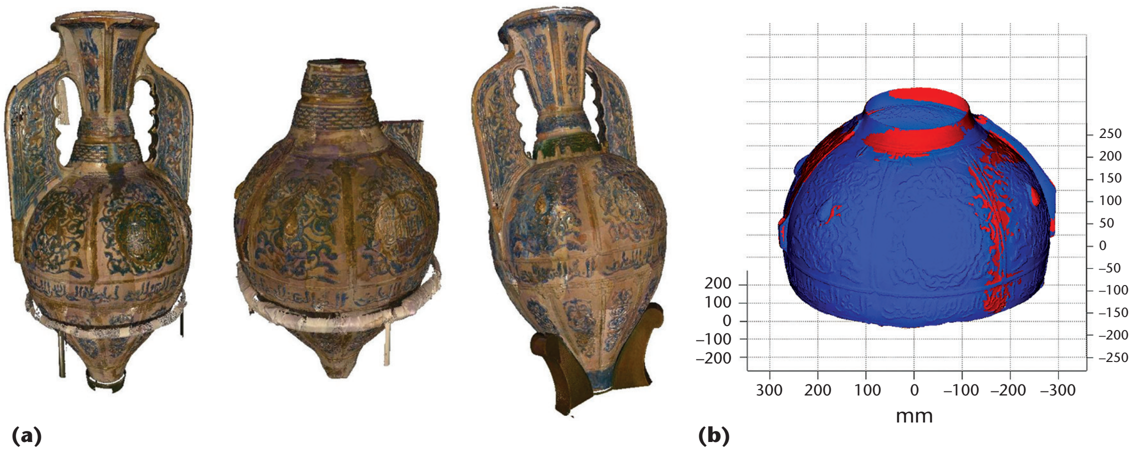


Figure 8. Comparing three Islamic vases from the Louvre. (a) The actual vases. (b) Alignment of 3D digital models of two of the vases. The blue areas indicate that the surfaces are within 5 mm of each other; the axes show the vases' dimensions. After digitizing the vases in 3D, curators believed this demonstrated that, to within manufacturing tolerances, they were from the same mold. (Images © C2RMF and 3D-COFORM; used with permission.)

nature of the research poses the question, what new types of analyses and cultural research can we perform if we have digital surrogates for the artifacts?

Islamic Vases at the Louvre

Decorative objects might look similar, but it can be difficult to say with certainty that the same artist or workshop made them. In the past, researchers compared hand-drawn tracings of the decoration. However, this was often tricky, hampered by the relief decoration and the glaze's reflective luster, and open to human error.

Curators in the Louvre's Department of Islamic Antiquities wanted to determine whether three vases acquired through different channels actually came from the same mold. They knew that one of the three—the Rifaat vase—had been produced in Granada, Spain, during the 14th or 15th century. After digitizing the vases in 3D, they virtually removed the color and glaze to compare the underlying surfaces. They demonstrated that to within manufacturing tolerances, the vases were from the same mold (see Figure 8).

This experiment has broader implications for curatorial practice. If cultural objects were routinely digitized and shape-based search was available, new opportunities would exist for investigating links between objects. For example, the same systems might help identify stolen artworks. However, the practicalities behind the simple phrase "routinely digitized" are extremely challenging, as I discuss later. Figure 9 illustrates shape-based search using a tool developed by Luc van Gool's teams at the Catholic University of Leuven and ETH Zurich as part of the 3D-COFORM project, based on their work with Hough transforms.[34]

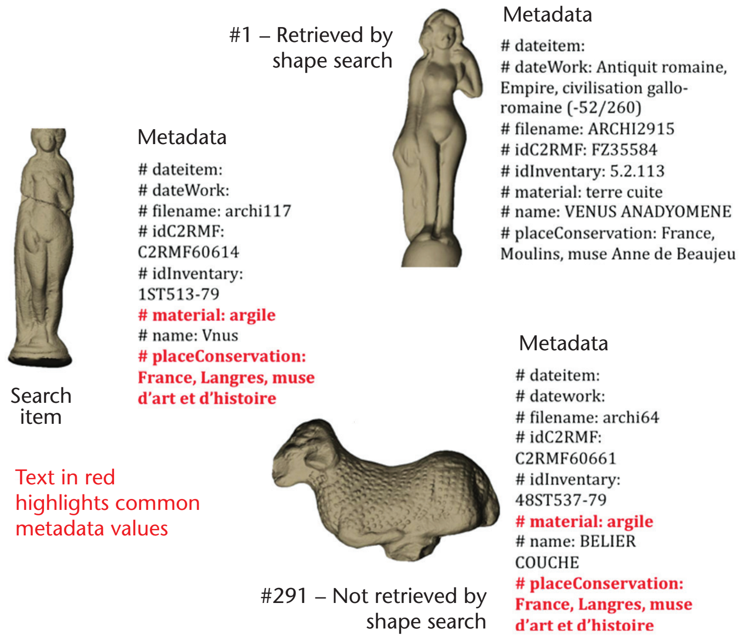


Figure 9. Shape-based search. The figurine on the left is the search item; the two on the right are candidates. Typical search functions would compare the search item's metadata with the candidates' and retrieve the bottom-right candidate, which is a poor match in terms of shape. Shape-based search classifies the objects according to some shape-based characterization; in this case, it retrieved the upper-right candidate. (Images © Katholieke Universiteit Leuven and 3D-COFORM; used with permission.)

The Van Dyck Portrait

A portrait of the 17th century Flemish artist Anthony van Dyck was believed to be by his teacher Peter Paul Rubens. However, research into its style and composition suggested it might be an early self-portrait.[35] To study the painting, art historians employed 3D scans by the MiniDome, analysis of historical manuscripts, chemical analysis of the paint, and even computed-tomography scans. When the 3D digitization is viewed under oblique lighting, the brushstrokes are thrown into relief, allowing reworked areas to be seen in greater detail.[12]

The Challenge of Digitization

Technologies to support cultural heritage have far to go. We need progress in coping with the scale of activity and complexity of materials before digital documentation is seen as the normal, routine approach to recording all we know about tangible cultural-heritage objects. On one level, the huge volume of cultural objects, even in formal collections, challenges the most ambitious plans for digitization campaigns. Possibly even greater practical challenges relate to the fact that probably 90 percent of museum collections are in storage and are inaccessible to the public.

On one level, the huge volume of cultural objects, even in formal collections, challenges the most ambitious plans for digitization campaigns.

For example, of the V&A's 2.24 million objects,[36] only over 10 percent are considered suitable for long-term display, and approximately only 2.5 percent are typically on view. The remainder are either artifacts in storage or library items. Yet the V&A collections were established specifically as an education resource to inspire future designers, which implies accessibility. Even these numbers are dwarfed by the Smithsonian's 137 million objects.[37]

A digital archive could not only serve as a record of holdings but also provide wider access. However, the transition to digital assets will require orders of magnitude improvement in productivity and a sustainable strategy for long-term preservation of the resulting resources.

Many computer scientists might instinctively consider rising to such a challenge through automation or semiautomation. This reaction needs reining in to consider the intensely practical question of whether such digital resources would achieve the expected benefits of access. Taken to a logical conclusion, every find in an archaeological site should be digitized, along with the settings in which it was found. And all these resources will need to be documented, preserved, and migrated to new archives. One site might produce 250,000 artifact fragments (for example, see Figure 4). So, we would have to evaluate how many fragments are worth documenting this way or whether the effort in being selective outweighs the economies achieved through reduced volumes.

The sheer scale of the digitization campaign implied by the report *The New Renaissance* is staggering. The concept of "all European heritage" (the collections in museums, libraries, and archives) involves an estimated "77 million books, 24 million hours of audiovisual programs, 358 million photographs, 75.43 million works of art, [and] 10.45 billion pages of archives."[4] Recording these items over the anticipated 10 years would involve digitizing five books, two hours of audiovisual content, 25 photographs, five works of art, and 2,000 pages of archives every minute.

On top of the incredible orchestration and throughput this implies, experiments suggest that the curatorial imperatives for recording metadata and following appropriate object-handling protocols would take even more time than the digitization itself.[38] Finally, the campaign would by definition be never-ending. Our heritage is continually augmented, not just because we add to it but also because the meaning of the existing heritage undergoes continual reinterpretation and evolution.

Such an undertaking would be truly enormous, and some would say it's unachievable. However, the visions of many thought leaders, and the rhetoric they encourage in policy makers, appear to be based on the assumption that such challenges will be met. "When all the museums of the world have their collections online ..." is a typical precursor of a vision of the future.

Is the challenge of completely digitizing cultural heritage a naive, unachievable ambition of dreamers or merely an extremely difficult logistics exercise? Either way, the volume of digital cultural data is rising, probably representing another manifestation of Moore's law. In other words, the volume of cultural-heritage data probably doubles in a short time, continuously as we record more and we individually and collectively add to our heritage. Part 2 of this article will examine the new types of analysis and the new applications that the availability of such large quantities of data could enable.

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