INTRODUCING 3D VISION AND COMPUTER GRAPHICS TO ARCHAEOLOGICAL WORKFLOW
An Applicable Framework

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Abstract: Cataloging drawings of ancient vessels and sherds is still the most time consuming task in the typical archaeological workflow. The properties of these findings like profile, volume, and wall thickness have always been estimated and drawn by hand. Through archiving, classifying and exhibiting these ancient artifacts we wish to gather as precise information as possible. Within seconds, today's 3D-scanners provide surface meshes of ancient vessels which are more precise than any manual estimation which may take up to several hours.
We propose a semi-automated, applicable framework for dealing with large 3D-meshes of ancient findings from scanning the vessels for publication. In this interactive environment we estimate the axis of vessels, estimate their profile lines and render real time visualizations using state-of-the-art 3D-hardware techniques. The results can be printed in their real size for direct use in archaeological literature. Further, these methods will give the ability to publish 3D-meshes of ancient vessels for archaeological research.
Recent extended tests have been carried out on archaeological sites in Peru and Austria. These experiments showed under real life circumstances the improvement of using this system in both precision and time efficiency.

1 INTRODUCTION

Motivated by the requirments of archaeologists we are developing a system for automated documentation of their finds. Beside (large) remains of architecture the most common finds on archaeological excavations are (small) objects of the daily live. These small objects are typically tens of thousands of fragments of ceramics (sherds), because ceramics have been used and preserved for thousands of years. Therefore documentation of sherds is one of the important tasks for archaeology, because sherds represent information about population movements, inter-regional contacts, production context, and technical or functional constraints (archaeometry (Leute, 1987)).

Until present day documentation is done by manually drawing a horizontal cross- section of the orientated sherds and a side-view of the ceramic. The horizontal cross-section is called profile (line). Furthermore the profile line is also the longest elongation around the wall of a ceramic. Therefore it is estimated the maximum height of a ceramic. An example for such a manual drawing is shown in Figure 1. While the right-hand-side of this Figure shows the Profile, the left-hand-side shows a front view of the sherd as it would appear without any traces of wear, dirt or any other dis-coloration of long-time-storage.

Therefore we have identified two major tasks to

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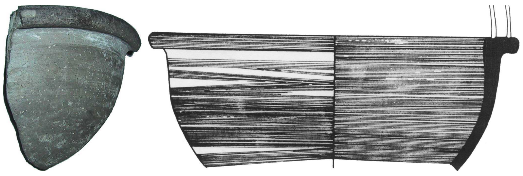


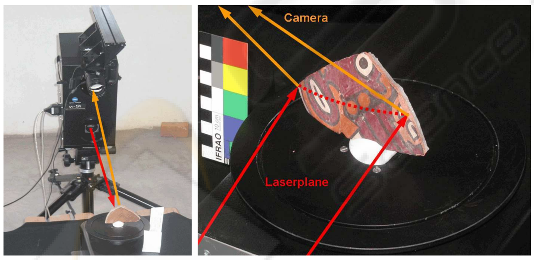
(a) (b)

Figure 1: (a) Photo of a real sherd and (b) its manual drawing showing the profile line.

be performed after 3D-acquisition of ceramics shown in the next Section. The first task is the estimation of the profile line shown in Section 3. Then we show a method for rendering the surface of acquired 3D-models adopted for archaeological publication in Section 4. In Section 5 we show results of our experiments applied to synthetic and real objects of excavations in Peru and Austria. Finally a conclusion and an outlook is given in Section 6.

2 DATA ACQUISITION

Depending on the skills of a craftsperson a manual drawing as shown in Figure 1 is done in 10 to 15 minutes for simple sherds. Regarding the vast numbers of sherds a large amount of working time on an excavation is spent on manual drawings. Therefore we are developing an automated system for acquisition of sherds and estimation of the profile-line. The acquisition is done by using a 3D-Scanner based on the principle of structured light (Cosmas et al., 2001) using a *Konica-Minolta Vi-900* or *Vi-9i* shown in Figure 2.



(a) (b)

Figure 2: In-situ setup of the 3D-scanner (a) consisting of a Laser, a CCD camera and a rotational plate for acquisiton of (b) e.g. a NASCA sherd found in the Valley of Palpa, Peru.

The rotational plate shown in Figure 2 is typically used for acquisition of unbroken ceramics for automated registration using ICP (Besl and McKay, 1992; Chen and Medioni, 1992; Rusinkiewicz and Levoy, 2001). In case of sherds, plates and other small objects either a model based approach (Kampel and Sablatnig, 2003) or a well defined frame (Mara, 2006) also acting as holding device can be used. Furthermore this frame is used to increase the performance of our system by acquiring severall sherds at once, as the 3D-Scanner requires fixed amounts of volume. Background objects and noise are removed either using their color (black/white) or by their size and/or location (Mara, 2006).

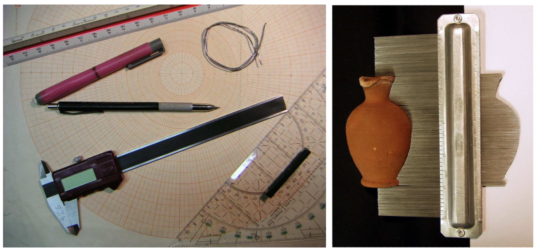
For testing the Profile estimation in the next section and for further interdisciplinary research to answer further archaeological questions we acquired severall hundred unbroken vessels and sherds in Austria (Lettner et al., 2006; Mara et al., 2007) and Peru (Mara and Sablatnig, 2007).

3 ORIENTATION & PROFILE ESTIMATION

Regardless if we are using a digital or manual system, the orientation of a sherd is the essential part of the estimation of the profile line as every further analysis (Leute, 1987) relies on it. Therefore this section shows how orientation is carried out by the estimation of the axis of rotation.

The oldest and most popular approach to orientation is the manual method used by archaeologists for several decades. This manual approach is based on the production process of ceramics, because ceramics have been produced on potters wheels (rotational plates) for thousands of years. Therefore ceramics have a axis of rotation, which is also called the axis of symmetry. This axis of rotation is also present for fragments of ceramics (sherds). Our method is inspired by a variation of the manual orientation, which is related to (Melero et al., 2003), because we also use the fitting of circle templates for the estimation of the axis. In contrast to (Melero et al., 2003) our method can be carried out both semi-automatically and automatically. Other related methods are (Willis, 2004) and (Orriols, 2004), which focus more on reconstruction of a complete, but broken object than on orientation of single fragments. Fitting of circle templates is done similiar to the manual method of archaeolgists. Therefore circles are fit into the inside of a sherd until the circle templates are concentric and their centers are aligned along the axis of rotation. This is achieved by fitting circle templates into the intersection between the sherd and sets of parallel planes. Figure 3a shows such circle templates and other tools to orient a sherd. Figure 3b shows a *Profilkamm* which is used to transfer the profile line to paper.

For the semi-automatic method these planes are aligned parallel to the XY-plane. The sherds have to be in upright position with an angular error less



(a) (b)

Figure 3: Tools for drawing a profile line: (a) pens, scale paper, lead-wire, ruler and sliding calliper, (b) *Profilkamm*.

than 20°towards and sidewards of the axis of rotation. The distance (radii) towards the axis of rotation is then estimated automatically. For the fully automated estimation of the axis the upright position is found in two stages: The first stage is the fitting of circles into intersections of sets of parallel planes orthogonal to the balancing plane of the inner side of the sherd. The normal vectors of the set of parallel planes having a minimum deviation of circle centers are aligned within the plane of symmetry. Figure 5 shows the inner side of a sherd with parallel intersections and a hypothesis for the axis of rotation (normal vector of the parallel planes). In the second stage this set of planes is rotated around the normal vector of the plane of symmetry until the minimum point of the deviation of the circle centers is found. The normal vector of the planes having this minimum point is used to transform the sherd into the upright position for the final estimation of the axis, which is identical to the axis estimation of the semi-automatic method.

As all these methods typically exist as matlab prototypes, which requires a license and computer expert skills for handling, we decided to implement the estimation of the profile line using open source technologies. Therefore we choose to implement our methods using *Qt*© (Trademark of Trolltech in Norway and other countries), which allows us to provide our framework for all actual major operating systems. Figure 5 shows a screenshot of our framework called *ArchiCut*. The next section shows how we achive a surface based rendering typically used together with the profile line within archaeological publications.

4 RENDERING CERAMICS FOR ARCHAEOLOGICAL DOCUMENTATION

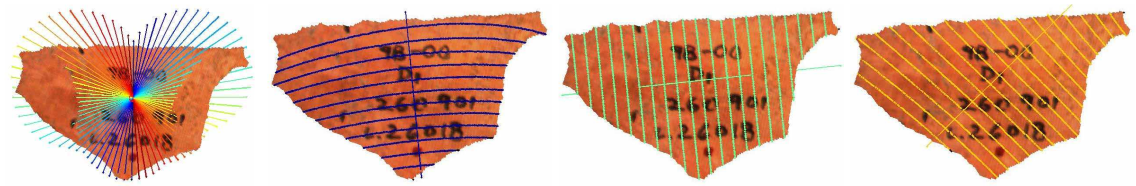
Having the profile-line automatically estimated as shown in the previous section, we achived to render the most important part for archaeological documentation of ceramics. Considering Figure 3b we have seen that archaeolgists add another important information about the ceramics: a side- view of the ceramic showing its surface, which is as important as the shape of the profile line, because the roughness and color of the surface leads to the manufacturing process and the ingridients of the clay.

Having a digital camera as part of the 3D-Scanner it is possible to acquire a still image or render the 3D-Modell with the texture acquired by the camera for the side-view of a ceramic. As simple this solution is for well-preserved finds - as unpracticable it is for archaeological documentation for the majority of sherds, because they are in general partially or completly discolored due to erosion. Therefore archaeologist generally favor a drawing over a still image or a photo-realistic rendering, because the drawings has a certain amount of abstraction showing the object with its original color. Furthermore, not every 3D-Scanner includes a camera capable of acquiring texture in color.

Therefore we require a simple and versatile concept to render the surface which does not include the colour information provided by some 3D scanners. It has to be simple, because having no texture requires a manual adjustment of reflectance parameters as templates for different ceramic surfaces. This has to be done by an archaeologist in an fast and intuitive way. Versatility is required, because we may also take into account the use of the naïve approach of measuring the reflectance of an existing material using a spectrometer and a robotic arm-setup that allows to freely move a spotlight and the spectrometer around the sample, and store them in an matrix. Such a device is called a ”gonioreflectometer” (Foo, 1997). Even by such a naïve approach storing the reflectance parameters in very limited space, while still giving an adequate appearance of many materials, such as velvet or lacquer can be achieved.

Suitable approaches to our problem, not limited to a certain domain are: The mathematical approach using a separable decomposition (Kautz and McCool, 1999), the phenomenological approach using the Lafortune BRDF (Lafortune et al., 1997) and the physically-based approach using the Cook-Torrance reflectance model (Torrance and Sparrow, 1967). An example for a limited domain is the Binn-Phong reflection, which is only used for rendering metals.

The rendering of the 3D data was supposed to take advantage of current graphics cards and to run predominantly on these dedicated graphics processors (GPUs). Because it could be done with minimal modifications to the prior source code and it is supported by all current hardware we choose to use the Graph-



(a) (b) (c) (d)

Figure 4: (a) Axes used for the first estimation of the rotational axis. These axes are defined by the masspoint and the balancing plane. (b) First Axis from (a) defined by the first eigen-vector of the balancing plane. (c) Axis defined by the second eigen-vector of the balancing plane. (d) Axis from (a) defined by the about 130° rotated first eigen-vector of the balancing plane.

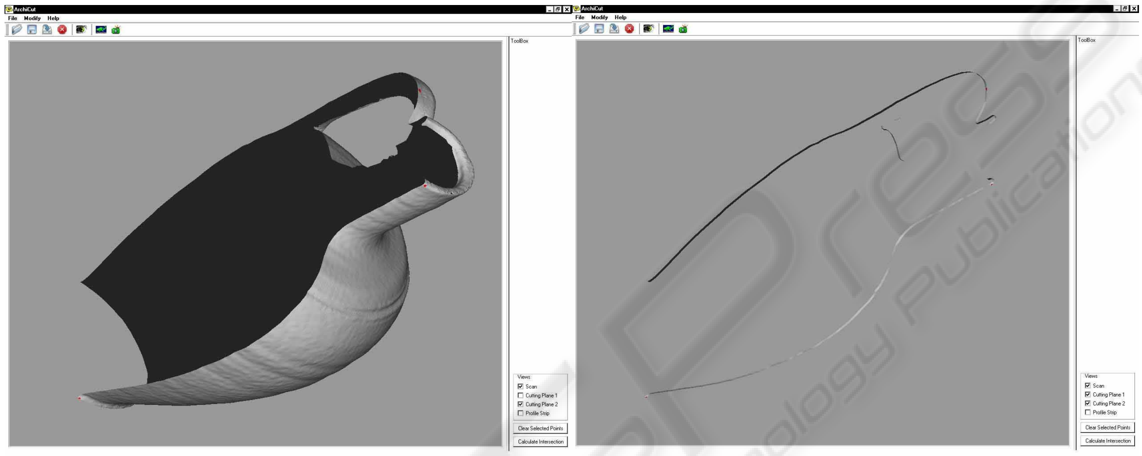


Figure 5: Screenshots ArchiCut - Left: Ceramics intersected through rotational axis. Right: Estimated Profile Line.

ics Library Shading Language (GLSL) programming language which is built into OpenGL 2.0. Taking this into account, we chose to include the Lafortune Bi-Directional Reflectance Distribution Function (BRDF) to our existing system done purely in GLSL.

Shaders were added to graphics cards, because the previous static rendering model (now called fixed-function pipeline) became more and more complex with each revision, in order to add rendering features like shadows or shading models. These features were implemented using a proprietary vendor-specific bytecode language. In order to allow more freedom to the graphics programmer, an open specification for shaders was created, extending the flexibility of the graphics card.

In the beginning, these shaders did not allow loops or conditions, since the graphics processor is a specialized stream-based processor, which allows it to be much faster at tasks that can be mapped to these constraints, compared to generic central processing units used in desktop computers. Beginning in shader model 3, loops and conditions were added at a great speed penalty.

4.1 Programming Shaders

GLSL (Shreiner et al., 2006) is designed in a similar way to all other high level shading languages available – namely, Microsoft's High Level Shader Language (HLSL) (Gray, 2003) and NVIDIA's Cg (Fernando and Kilgard, 2003). It is based on the C programming language, allowing software developers to leverage existing knowledge about it.

Shaders in the shader model 3 are are structured into two separate parts, a vertex shader and a fragment shader.

1. A vertex shader is responsible for transforming the vertices of the triangles sent to the GPU from the world space to the view space. It can move vertices, but it cannot add or drop them. Its main function is run once per vertex.
2. A fragment shader is responsible for defining the color of a fragment after the rasterization step. A fragment (in respect to the shader) can be described as a "potential pixel" on the screen. It might get culled after the shader is run, but if that doesn't happen, it is directly written to a pixel in the frame buffer. This allows using arbitrary shad-

ing, and is the location where the Lafortune BRDF used in this paper has to be implemented. It is run once per fragment, so it is important to keep this shader as simple as possible.

4.2 The Lafortune Shader

(Lafortune et al., 1997) demonstrates that an even approach simpler than (Kautz and McCool, 1999) can be used to adequately approximate a BRDF. Basically a BRDF reflectance function is a combination of multiple so-called "Phong Lobes" – or vice versa: The representation known as Phong reflection model is actually a simple but limited BRDF. Mathematically, the reflectance function can be represented as

$$L_o(\hat{\omega}_o, \hat{\omega}_i) = \rho_d + \sum_{i=1}^{M} \rho_{s,i} \cdot \left(\begin{bmatrix} \omega_{o,x} \\ \omega_{o,y} \\ \omega_{o,z} \end{bmatrix}^T \cdot \begin{bmatrix} C_x & & \\ & C_y & \\ & & C_z \end{bmatrix} \cdot \begin{bmatrix} \omega_{i,x} \\ \omega_{i,y} \\ \omega_{i,z} \end{bmatrix} \right)^n$$

where ρ_d is the diffuse reflectance (texture), M is the number of Phong Lobes, and $\rho_{s,i}, C_x, C_y, C_z, n$ describe the Lobe shape. So, considering that ρ represents colored information, the amount of memory required is $M * 7 + 3$ per surface. This small requirement enables storing a separate BRDF for each UV-coordinate of the object (using two additional textures per lobe). The results of this technique named "Spatial BRDF" (SBRDF) is demonstrated in images available on `http://sbrdf.cs.unc.edu` (McAllister, 2004) (checked 26.Sept., 2007), where more information is also presented.

The lobe shape described by C_x, C_y, C_z and n can be interpreted as follows: The C-parameters define the location of the reflection peak using a three-dimensional vector. n describes the spread of the highlight created by this lobe. Usually, only up to three lobes are necessary for visually pleasing result.

The ray tracer "pbrt" described in (Pharr and Humphreys, 2004) also implements the Lafortune BRDF (non-spatially). However, it allows specifying one BRDF per primary color, allowing a more realistic reflectance behavior, for the price of tripling the storage requirements. (Marschner et al., 1999) describes how to create primary-color-separated BRDFs by using a laserline scanner and a video camera.

The pseudocode used for calculating a fragment's color is shown in Listing 1. The algorithm's complexity is $O(n \cdot m)$, where n is the number of lights and m is the number of lobes.

Note that the implementation calculates the BRDF for the three primary colors separately, in order to further enhance realism and be able to integrate the example materials used in (Pharr and Humphreys, 2004) (not shown in the pseudo code).

Listing 1: Pseudocode for the fragment shader.

```
void main() {
 normalize normal vector
 calculate and normalize view vector ...
 based on the normal vector and ...
 the position of the fragment in ...
 world space

 fragment color = base color of the ...
 fragment derived from the vertex color
 for every light {
  light direction = normalized ...
  light position

  add diffuse color to fragment color
  // diffuse = light color * ...
  // object's diffuse color * ...
  // (N . light direction)

  if(fragment is visible from the ...
    viewer and light source is ...
    visible from the fragment) {
   uv = pointwise multiplication ...
   of the view vector and the ...
   light direction

   for every lafortune lobe {
    add the lobe reflection to the ...
    fragment color separately for ...
    each primary color
    // reflection = light color * ...
    // ((Cx, Cy, Cz) . uv)\^n
   }
  }
 }
}
```

The values Cx, Cy, Cz and n used for the lobes are specific to the material used and stored in a separate XML file (Bray et al., 2006) shipped with the application, which allows adding, removing and changing the presets without requiring a recompile of the application. The demo materials used were blue paint, brushed metal, clay, felt, primer and skin (see Figure 6).

4.3 Image Creation

The second part required for publications is the creation of an image based on the rendered image. A screenshot would not be sufficient for this, because the typical screen resolution of 100 dots per inch is too low, at least 300 dots per inch (preferably more than 600 dots per inch) are required for printed material. Thus, a more sophisticated approach is required.

The OpenGL extension called "Framebuffer Objects" allows replacing the screen's framebuffer with a texture-based one. This texture is not limited by the screen dimension, and thus can be any size up to the

(a) (b) (c) (d) (e) (f)

Figure 6: The demo materials rendered using the Lafortune Shader. From left to right: blue paint, brushed metal, clay, felt, primer and skin.

maximum texture size allowed by the graphics card (currently, this is 8192×8192 pixels). After rendering into this texture, it can be copied from the graphics memory to the main memory, encoded in an image format like PNG or TIFF, and saved to the disk.

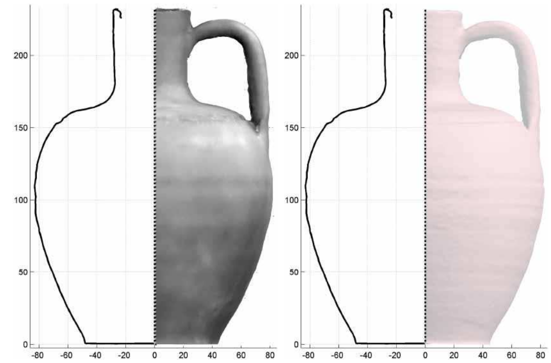
The first implementation created a 8192×8192 texture, and rendered into it. As mentioned earlier, the real dimension of the object is known (per convention, laserline scanners use a millimeter unit scale for their data files), since orthographic projection is used. So, the resolution is stored into the file, if the format supports that metadata. However, this results in unequal horizontal and vertical resolutions if the object isn't square, or phrased differently, non-square pixels. Tests revealed that many graphics processing applications including Adobe Photoshop (which is the post-processing application used by the archeologists) cannot handle non-square pixel graphic files. Thus, a second revision was created, that scales portrait objects to a height of 8192 pixels while setting the width according to the vertical resolution, and vice-versa for landscape objects. This reduces the resolution in one dimension slightly, but is still sufficient for the objects usually scanned by the archeologists. Due to the fixed size of 8192 pixels, the actual resolution of the image depends on the object's physical size.

5 RESULTS

For a first glance of results of our transdisciplianry work in cooperation with archaeologists, we could directly answer their questions for objective/precise and rapid documentation. This means for examples: we are the first to publish new volume of the *Corpus Vasorum Antiquorum* (CVA) – a very well established book series in classic archaeology for a century (Pottier, 1923) – using 3D-acquisition and our proposed methods. This work includes digital profile lines with side/top-views as shown in this paper. Additionally unwrappings of textured surface including multispectral readings (Mara et al., 2007) and volume estimations were conducted. We could also decrease the costs for acquisition as less working time was required. Furthermore the risk for damaging this high-value objects was minimized, as 3D-acquistion using optical means takes only a few seconds and requires a minimum of (in-situ) handling the objects.

Another recent example are the results for the vessels excavated in the Valley of Palpa, Peru. In this region the wheel was not invented and therefore the assumption of an rotational axis for ceramics may not be valid either. Allthough we could determine axis and planes of symmetry giving the archaeologists quality features for further classification. Furthermore we could unwrap and enhance the pictoral information of the painted vessels (Mara and Sablatnig, 2007).

The final result of our work is the collection of methods as application framework called *ArchiCut*, which completly relies on Open-Source to achive transparency and cost-effectivness of the archaeolgical workflow. A screenshot of the User-Interface is shown in Figure 5, while Figure 7a shows the combined result for the profile line and a scaled side-view render as clay, while Figure 7b shows a typically improper rendering - as 3D-scanners may not acquire correct reflectance nor any texture nor colour information at all. As there already exists software for editing 3D-data, we choose to implement an import function using human- readable ASCII files (*Wavefront .OBJ*). Furthermore data can be directly acquired from *Polyworks, InnovMetric Software Inc.* – a commonly used 3D- editing software – to increase the performance of the workflow.



(a) (b)

Figure 7: Rendering of the profile line and the matching side-view: (a) Arbitrary surface properties giving the impression of a glaced pot. (b) Clay rendering reassambling a clean and synthetic, but realistic impression.

6 CONCLUSIONS AND OUTLOOK

Concluding and summarizing this paper, we are able to show the application of 3D Vision and Computer Graphics to archaeology within very different research fields: From South American (”prehistoric”) to Roman findings and for small fragments up to complete large objects. While 3D-acquisition can already be done by off-the-shelf products, for post-processing like noise removal and registration there exist a vast amount of algorithms. Although there is still much space for improvment, state-of-the-art methods already suit archeolgist’s purposes as we showed in large scale experiments. The main part of this publication concerns with the orientation of non-industrialized objects and their fragments, which are supposed to be rotational symmetrical. Therefore we could show a method for orientation based on disturbed symmetry to estimate the profile line – the most important part of archaeological documentation of ceramics. Followed by real-time-rendering of the objects surface adopted for archaeolgical documentation, which requires high-resolution for printing and spatial information for further research. This information is merged with the profile line to complete the documentation. Furthermore the surface properties can easily be adopted and stored as templates as the real texture is either not acquired by certain types of 3D-scanners or it merely contains noise – typically dirt.

Future work will be the integration of novel methods into our framework, which are currently under ongoing development. These methods concern the processing, (pattern) recognition and rendering of decorated surfaces. Furthermore we will investigate towards symmetry analysis, which e.g. lead to answers about other important archaeological questions about manufacturing processes and quality features for differnt types of ceramics and their classification.

Beside all the previously mentonied improvements of methods another important – conceptual – work has begun to ensure the intellectual integrity, reliability, transparency, documentation, standards, sustainability and accessibility of the information gathered by the increasing use of 3D-scanners. Otherwise we will face the problems shown in (Ogleby, 2007). Therefore we are adopting *The London Charter* (Beacham et al., 2006), which will be a future standard for the use of 3D- Vision and Computer Graphics within Cultural Heritage.

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