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# Challenges and Directions in 3D and VR Data Curation: Findings from a Nominal Group Study

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**Abstract**

This study identifies challenges and promising directions in the curation of 3D data. 3D visualization shows great promise for a range of scholarly fields through interactive engagement with and analysis of spatially complex artifacts, spaces, and data. While the new affordability of emerging 3D capture technologies presents greater academic possibilities, academic libraries need more effective workflows, policies, standards, and practices to ensure that they can support the creation, discovery, access, preservation, and reproducibility of 3D data sets. This study uses nominal group technique with invited experts across several disciplines and sectors to identify common challenges in the creation and re-use of 3D data for the purpose of developing library strategy for supporting curation of 3D data. This article identifies staffing needs for 3D imaging; alignment with IT resources; the roll of archivists in addressing unique challenges posed by these datasets; the importance of data annotation, metadata, and transparency for research integrity and reproducibility; and features for storage, access, and management to facilitate re-use by researchers and educators. Participants identified three main challenges for supporting 3D data that align with the strengths of libraries: 1) development of crosswalks and aggregation tools for discipline-specific metadata models, data dictionaries for 3D research, and aggregation tools for expanding discovery; 2) development of an open source viewer that supports streaming and annotation on archival formats of 3D models and makes archival master files accessible, while also serving derivative files based on user requirements; and 3) widespread of adoption of better documentation and technical metadata for image capture and modeling processes in order to support replicability of research, reproducibility of models, and transparency of scientific process.

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## Introduction

3D visualization technologies show great promise for a range of scholarly fields as they offer new potential for interactive engagement with and analysis of spatially complex artifacts, spaces, and data (Angulo, 2013; Donalek et al., 2013; Jang, Vitale, Jyung and Black, 2017; Laha, Bowman and Socha, 2014; Ragan, Kopper, Schuchardt and Bowman, 2013; Seth, Vance and Oliver, 2011; van Dam, Laidlaw and Simpson, 2002). While the new affordability of emerging 3D capture technologies presents greater academic possibilities (Chapman, Baldwin, Moulden and Lobb, 2013), academic libraries need more effective workflows, policies, standards, and practices to ensure that they can support the creation, discovery, access, preservation, and reproducibility of 3D data sets. While many libraries have developed archives and policies for preserving and managing other forms of research data, there is a notable absence of standards and best practices for producing, managing, and preserving 3D content within the digital library community (Koller, Frischer and Humphreys, 2010).

Scholars in a range of fields are already incorporating 3D technologies into their research practices, using them to enhance their methods of analysis and produce new types of scholarly outputs. Recent advances in computational hardware, along with lower costs, have further expanded the accessibility and practicality of using 3D technologies, such as photogrammetry and laser scanning, in a variety of research and educational contexts. For fields such as architecture and engineering, 3D methods have become standard practice, and there is growing interest in fields such as archaeology and cultural heritage preservation (Limp et al., 2011).

Meanwhile, virtual reality (VR) systems are becoming a powerful tool for visualizing and analyzing 3D research data, thanks to advances in both quality and affordability. 3D data is widely deployed in software- and browser-based "flat" systems. Even expensive CAVE systems have presented immersive VR experiences for the computer science departments that can afford them. Now, a new wave of cheap VR equipment presents exciting new possibilities for displaying 3D data in interactive, stereoscopic 3D displays for a range of disciplines and institutions.

Given this growing interest, more guidance is needed for broader integration of 3D technologies into research practice with attention to issues such as sustainability of software and file formats, cost modeling, and personnel requirements. Metadata schemas and recommended file formats are especially critical for supporting data reuse, reproducibility, and transparency in research applications of 3D (Koller, Frischer and Humphreys, 2010). Such documentation provides contextual information in support of digital preservation (Beaudoin, 2012) and is an essential component for managing the digital curation lifecycle[1].

In order to develop a base of knowledge to address these concerns, an inter-institutional team from Virginia Tech, Indiana University, and University of Oklahoma hosted a forum in Washington DC March 1-2, 2018 as part of the IMLS funded Developing Library Strategy for 3D and Virtual Reality Collection Development and Reuse (LIB3DVR)[2]. The forum brought together invited experts from universities, government agencies, public libraries, corporations, and non-profit cultural heritage institutions in pursuit of the following goals:

1 DCC Curation Lifecycle Model: http://www.dcc.ac.uk/resources/curation-lifecycle-model
2 IMLS LG-73-17-0141-17: https://www.imls.gov/grants/awarded/lg-73-17-0141-17

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- Develop strategies for libraries to support 3D curation, creation, and use throughout the research lifecycle – including metadata schemas; workflows and tools for capturing metadata from content creation through visualization, archiving, and reuse; and repositories that enable description, discovery, and long-term preservation.
- Establish guidelines that can serve multiple research contexts and use cases that libraries may need to support as researchers increasingly adopt 3D technologies for research.
- Develop strategies that libraries can use to develop policies and workflows to support research services for 3D data, such as preservation, discovery, and access.

Other recent and concurrent projects are working to produce knowledge in the same area, including the PARTHENOS Project, Community Standards for 3D Data Preservation, Building for Tomorrow, and the Web3D Consortium. The European-based PARTHENOS Project[3] recently published a report focused on 3D creation, interoperability, and preservation in the arts and humanities, with primary applications for the field of museology. A major theme of this work is the importance of researchers and professionals producing clear guidelines and documenting their own research practices starting from digitization and modeling stages all the way through archiving and description stages of working with 3D data. The PARTHENOS findings are derived from a series of expert-led workshops that were held in Bordeaux, France in 2016. PARTHENOS conceptualizes 3D models within cultural heritage paradigms of preservation, but there is still a gap in knowledge around scientific and other 3D applications that are of interest to a broad and growing body of researchers. For this reason, very little interdisciplinary consensus exists concerning content creation workflows, metadata schemas, repository structures, and file formats for preservation.

Community Standards for 3D Data Preservation (CS3DP)[4] is another IMLS-funded project[5] that is currently working to develop community standards for 3D data preservation in academic research contexts. This group is working towards a community-developed plan to move 3D preservation, documentation, and dissemination forward by laying the foundation for an organized community of practice to develop and move forward on shared standards for 3D data preservation. CS3DP is a collaboration between Washington University in St. Louis Libraries, University of Michigan Museum of Paleontology, and the University of Iowa Libraries. This project convenes leading experts and key stakeholders, including librarians, curators, faculty, and information professionals from organizations across the U.S. and abroad to address the issues of digital 3D data preservation. Project partners from CS3DP and LIB3DVR are participating in each other's projects to enable collaboration and engagement between the projects on the issues of standards development and implementation within library workflows. As will be seen in Findings (below), some similarities in scope and shared participants led to some conversations beginning at CS3DP and continuing in LIB3DVR forum meetings.

Another major grant-funded project currently addressing a similar problem area is the IMLS-funded project, Building for Tomorrow: Collaborative Development of

3 PARTHENOS: Pooling Activities, Resources and Tools for Heritage E-research Networking, Optimization and Synergies: http://www.parthenos-project.eu/

4 CS3DP: Community Standards for 3D Data Preservation: https://osf.io/ewt2h

5 IMLS LG-88-17-0171-17: https://www.imls.gov/grants/awarded/lg-88-17-0171-17

Sustainable Infrastructure for Architectural and Design Documentation (LG-73-17-0004-17)[6]. For this project, the Frances Loeb Library at the Harvard University Graduate School of Design convened two priority-setting meetings of stakeholders, including architects, architectural historians, archivists, librarians, technologists, digital preservationists, and others, in order to define a national/international collaborative infrastructure to support long-term preservation of 3D digital design data in the architecture and design fields.

Finally, while the examples above are term-limited projects, the Web3D Consortium[7] is an international industry-standards-setting organization that develops and promotes technical standards for web-based 3D graphics. This body created and now maintains and supports the X3D (Extensible 3D) format, an ISO-IEC (a joint technical committee of the International Organization for Standardization and the International Electrotechnical Commission) ratified, royalty-free open standards file format and run-time architecture to represent and communicate 3D scenes and objects[8]. This standard evolved from the Virtual Reality Modelling Language (VRML), another Web3D Consortium standard ratified by the ISO-IEC that is forward compatible with X3D. X3D is a promising standard, and there is much work to do to integrate it into 3D creation and reuse workflows across disciplines.

While these projects have all proven valuable in their own ways, until recently there was little effort to coordinate or communicate across disciplines on the interrelated issues of curation, preservation, and display of 3D data. While some of the research described in this paper overlaps in scope, rationale, and objectives with the projects cited above, the findings presented in this paper are just a subset of findings derived from the other LIB3DVR forums on library strategy for the development of 3D services for content creation and publishing; visualization and analysis; and repository practice and standards. The findings from the Washington DC forum on content creation and publishing are the topic of this paper.

# Methods

The conveners assembled a two-day forum in Arlington, Virginia with 22 participants representing academic librarians, public librarians, researchers from diverse fields (computer science, biomechanics, paleobiology, history of architecture), non- profit cultural heritage imaging professionals, public sector imaging professionals (from the Library of Congress and the Smithsonian), and commercial vendors of 3D imaging hardware. The invited researchers represented large public and private universities as well as private liberal arts colleges and public libraries.

The conveners used a nominal group technique (McMillan, King and Tully, 2016) to reveal key challenges in the production and dissemination phases of the 3D data lifecycle and to identify and develop capacity and community to address those challenges. Nominal group technique is a consensus-building method for achieving general agreement on a topic through face-to-face small group discussions. It is useful for understanding stakeholder views.

The conveners arranged the participants into small groups and prompted them with questions that generated recommendations in the following categories:

6 IMLS LG-73-17-0004-17: https://www.imls.gov/grants/awarded/lg-73-17-0004-17
7 Web 3D Consortium: Open Standards for Real-Time 3D Communication: http://www.web3d.org/
8 What is X3D? http://www.web3d.org/x3d/what-x3d

- 3D scanning and modeling
- Storage, access, and management
- Integration of 3D data into existing research and scholarly communication services
- Metadata requirements

For some prompts, the attendees were told to form professionally diverse groups, where each table had an even distribution of each type of participant. For other prompts, the attendees were told to form groups where everyone had a similar professional affiliation.

One member of the project team joined each group to facilitate discussion and take notes. The participants were also able to take community notes through a shared online document that was set up in advance. The smaller groups then reported back to the larger group for broader discussion and consensus building. Notes produced from the smaller groups and from the larger group form the basis of the findings. We validated these findings by disseminating an early draft of this paper to participants, who then offered clarifications of certain points, or elaborated further on them. The authors incorporated all participant feedback into a subsequent draft.

The authors acknowledge some methodological limitations to this study. First, the grant only funded domestic travel, which restricted international representation in the forum meeting, potentially leaving out some key stakeholders and bases of knowledge from ongoing 3D research projects in Europe. Furthermore, the findings reported here only represent the perspectives shared by the participants at the forum, and thus may not be generalizable to stakeholder groups not included in the proceedings. While the authors are confident in the participants' expertise and the diversity of viewpoints represented through the selection of participants, nominal group technique imposes limitations on the size and diversity of the groups, which places restrictions on the number of perspectives that can be captured at once.

This study was approved by Virginia Tech's Institutional Review Board (18-770).

# Findings

This section organizes the findings into subsections that align with each topic from the forum agenda.

## 3D Scanning and Modeling for Reuse

### Program planning and resources for reuse

A variety of staffing needs to support creation and management of 3D and VR data emerged from the conversation, and these requirements may vary depending on the program's mission and funding. The major sub-themes that emerged included the importance of aligning with IT resources; the need for expertise in multiple fields; importance of working with archivists to address the challenges posed by the large scale of 3D datasets; and the importance of transparency for research integrity and reproducibility.

### *Alignment with IT resources*

Due to the high storage and processing requirements of 3D modeling, it is important to have close alignment with available Information Technology (IT) resources during the program design phase. In photogrammetry, a single 3D model requires hundreds of high-resolution images. Depending on the required level of detail and depth of field for some artifacts and specimens, certain techniques such as focus stacking could result in thousands of high-resolution photos to generate one 3D model. A stable and robust IT environment is crucial.

### *Multi-disciplinary expertise*

Some participants felt that a successful photogrammetry program requires expertise in multiple fields. For instance, one firm had an expert photographer and a texturing artist or 3D modeler on its photogrammetry team. The 3D modeler was needed for correcting imaging artifacts, such as gaps in the model where the imaging hardware or software missed some detail or feature. While libraries and IT teams sometimes have graphic artists and web designers on staff, 3D artists with deep knowledge and requisite skills in this area for photogrammetry are rare, more commonly associated with film and video game industries. It may be difficult for a library to attract and retain employees with those skill sets, but it might be possible to work with these skilled artists on a freelance or contract basis. It should also be noted that for academic and cultural heritage sectors, such augmentations are not permissible in other digital workflows as they require subjective interpretation of the item being digitized. In such contexts, if these adjustments are deemed necessary, they should be documented as an artifact of current imperfect technology, which will be overcome with future advances in imaging techniques and technology.

### *Archival challenges*

Archivists and data managers can provide unique assistance in cases where there is a lot of data, and where data reuse and transparency are important. For example, two participants who manage morphology labs at large research universities generate enormous volumes of data (terabytes) per week. For them, the question is not simply how to retain data, but what to retain and how much to retain. Keeping all of the data might not be necessary or financially efficient. Digital archivists and data management specialists, working in close partnership with researchers, can help with data selection and appraisal, determining which parts (and how much) of the data it is necessary to retain in order to rebuild and verify the accuracy of 3D models. These roles may not be as important for maker spaces, animation studios, and other types of studios where the mission is not tied closely to transparency, reproducibility, and the scientific record.

### *Research transparency, integrity, and reproducibility*

Some aspects of 3D production and preservation for science are particularly difficult to manage, especially when it comes to transparency. Many of the tools for 3D modeling, such as laser scanners, are a "black box" in that the algorithms used to derive point clouds, mesh maps, etc., do not transparently document data capture and data transformations in the same way as other imaging technologies. Transparency requires documenting the decisions made, the tools used, and the rationale for these choices so that other researchers can evaluate the accuracy and the integrity of the 3D creation process. While imaging hardware and software may be able to generate a persistent standardized file format for archiving and re-use, the lack of transparent methods inhibits scientific reproducibility. This is a serious problem in morphology where subtle differences between specimens reveal new knowledge about diversity and distribution of historic plants and animals. Therefore, researchers require best practices for preserving output for later use. Similarly, when models require editing, there is an absence of standards for documenting how researchers massage or manipulate 3D data in order to make it more visually accurate than what the hardware and software capture. Ideally, all adjustments to the model are noted in metadata and reversible through layering or file versioning.

Photogrammetric capture addresses the transparency issue in part because the raw data are in standard image formats (TIF, RAW, DNG) that support embedded Exif metadata, such as date and time of creation, ISO speed, focal length, shutter speed, aperture. Maintaining these original image files with their Exif data provides documentary evidence of the conditions in and methods with which the raw data is collected. Other 3D modeling technologies do not capture these data. While the modeling software algorithms used to translate images into 3D data points may not be transparent, research can be verified by reconstructing models from the original images. Another strategy for addressing the problem of documentation and reproducibility is the incorporation of the X3D standard (extensible 3D, previously discussed) into research and archival workflows.

This section has described several teams or sets of professional skills that are important for 3D scanning and modeling. For a digitization project, much of the work may occur in an ordered sequence. For 3D programs that digitize a large number of specimens or artifacts, perhaps from multiple collections and sources, there is potential for congestion or slowdown in processing at certain stages. Forum participants discussed the importance of team members with skills in project management and process management to prevent such bottlenecks.

Both software and hardware options are useful to note since funding resources might impact use or support for some systems over others, especially in the case of libraries that might need less expensive options that or options that do not require much physical space. Software needs that emerged in the discussions included Unity, RealityCapture, Blender, Substance Suite, Adobe Suite, Agisoft Photoscan, Zbrush, Knald or Xnormal, MeshLab, InstaLOD, and GEOMagic, but it should be noted that these requirements are contextual based on the nature of the 3D work being done. Necessary hardware included digital single-lens reflex (DSLR) cameras, as well as the components that might go with them. Some setups were as simple as a single DSLR camera on a tripod aimed at a turntable on a copy stand. More complicated and automated systems could include a full photogrammetry rig with multiple synchronized cameras mounted on portable or set frames. Other techniques discussed utilized proprietary laser or structured light scanning equipment.

### Cost, value, and challenges of CT/volumetric capture

Volumetric data derived from computerized tomography (CT) scanning and other modalities has tremendous potential in a variety of disciplines. Unfortunately, the cost is still prohibitive for most labs, much less libraries. Medical research uses volumetric scanning through CT. For cultural heritage digitization, certain imaging methods and technologies are impossible. In some cases, objects cannot be moved to the scanner because they are fixed in place, large, sensitive, and/or protected. Examples include archeological sites, cultural properties, geographic features, and endangered artifacts or species. In extreme cases, the artifact is destroyed and 3D modeling can only rely on crowd-sourced photogrammetry.

Many challenges were discussed in supporting workflows to create 3D digital objects within the library context. Standardizing open file formats and using as transparent a process as possible are the ideals but the library community will need to be a vocal part of the larger 3D community to see these recommendations become reality. Participants identified open source software applications such as Blender and MeshLab, which may be useful alternatives for certain steps of the modeling process, and adoption of open source software would improve transparency in the algorithms for editing 3D data. From there, the forum agenda moved to discussing storage, access, and management of these 3D digital objects that are being created.

## Storage, access, and management

Another discussion session focused on resources for storage, access, and management—particularly in the context of re-use by researchers and educators. This session was preceded by a brief demonstration of Morphosource[9], a 3D image archive of zoological and anthropological specimens based at Duke University. The demonstration was used to generate discussion and ideas. Attendees thought Morphosource was impressive, with the caveat that it requires some domain mastery making it less useful for K-12 environments. For example, browsing features required knowledge of taxonomic classification. Proprietary platforms for 3D model sharing such as Sketchfab and Thingiverse significantly lower the barrier for access to broader audiences, yet do not adequately serve the needs of researchers.

Most of the participant discussion focused on identifying the strengths and features of existing platforms that might be combined to create a platform that allowed for rigorous analysis but would also appeal to lay audiences. Alternatively, some participants felt that, because each system is strong at a specialized task for a specific community, it would be better to make the existing platforms more interoperable rather than creating a single platform that does everything. For example, if there were ways to aggregate or link from models and data sets on sites like Smithsonian 3D and Morphosource, along with models from proprietary sites like Thingiverse and Sketchfab, then research communities could benefit from the robust features of some platforms. Meanwhile lay communities could benefit from the accessibility and re-use features, such as being able to download and print models, or embed them in other websites via iframe. Ultimately, the goal would be to analyze data and make annotations on one platform, disseminate it to the public in another platform, and, if desirable, push it to a third platform that specialized in printable models. It is outside the scope of this paper to recommend any one of these strategies over another. We present these options just to document the discussions among the participants. The rest of this subsection will discuss useful features for enabling 3D model reuse.

Some participants were interested in the fact that the Digital Public Library of America (DPLA)[10] and iDigBio[11] both support access by aggregating metadata from collections, thereby reducing research silos and improving distribution of collections (although neither of these platforms currently supports 3D models). Another concern with access and management is the ability to produce consistent documentation of provenance. Some participants wanted ways for users to know which institutions house the original resources that 3D models are derived from. For example, the NIH 3D Print Exchange (Coakley et al., 2014) allows provenance to be embedded in the file's

9 Morphosource: https://www.morphosource.org/
10 Digital Public Library of America: https://dp.la/
11 iDigBio: Integrated Digitized Biocollections: https://www.idigbio.org

metadata. Among European museums, a community of practice has emerged using the CIDOC CRM standard for searching across heritage artifact collections, but this practice has not been established in the United States. Finally, there was also discussion about different ways of managing access to sensitive collections. The Mukurtu[12] platform offers multiple authentication levels that are useful for controlling access to cultural heritage objects from indigenous communities. To summarize this part of the discussion, participant suggestions included functionalities such as searching by collections, searching across multiple collections, tracking provenance, and restricting some search results to within a collection and within a user community.

Some participants observed that certain proprietary online hosted platforms (e.g. Thingiverse and Sketchfab) may not support data transparency and research reproducibility, but they do lower the barrier for use, thereby making 3D content available for a broader population. Some of the research-oriented platforms are effectively siloed due to overspecialization, which results in relatively small user communities.

In spite of lower utility for research and preservation, the Thingiverse user community offers useful features that handle content versioning attribution with a metadata element for "modified by." While this metadata element is not unique to Thingiverse, its wide use in this community demonstrates the value of sharing and modifying work, while also documenting the modification. Participants felt this kind of version control of models is useful for other communities of users sharing 3D data.

Participants generally liked the access and licensing features of TurboSquid and CGtrader, which are marketplaces for buying and selling 3D models. Participants also liked the way that Fedora/Samvera handles storage. Participants liked Sketchfab's ease of use, especially with respect to embedding its viewer in other platforms, such as ContentDM, Omeka, and Open Journal Systems; still, they wished it were more sustainable and flexible. One shortcoming, for example, is the fact that Sketchfab is a commercial platform. Participants believed that is less stable in the long term than open-source software with transparent architecture. Other Sketchfab limitations the participants cited included file size limits and its branding of all content shared through it. Additionally, the lack of metadata obscures origins and sources of the models, which raises ownership and rights issues. 3D Heritage Online Presenter (3D-HOP)[13] is better at scaling higher resolution 3D models while browsing than is Sketchfab. 3DHOP, in conjunction with a tool called NEXUS,[14] can handle models with up to hundreds of millions of faces. Sketchfab's limits are based on file upload size and vary with user level (free, pro, premium, etc.). Participants had positive impressions of International Image Interoperability Framework universal (IIIF)[15] for its capability to host high-resolution content and dynamically derive lower resolution versions for optimized web display, which could serve as a model to improve 3D browsers. Participants also believed that this would facilitate sharing and comparison of 3D models.

Participants also liked Sketchfab's model inspector tool for its ability to make technical aspects of models more transparent. Data transparency tools in general are important for researchers in the re-use of 3D models. Useful platforms for researchers need to include technical metadata, either embedded in the model file itself, or in a separate technical report. In either case, technical metadata should document all

12 Mukurtu: http://mukurtu.org/

13 3DHOP: 3D Heritage Online Presenter: http://vcg.isti.cnr.it/3dhop/

14 NEXUS: adaptive 3D: http://vcg.isti.cnr.it/nexus/

15 IIIF: International Image Interoperability Framework: http://iiif.io/

specifications from the hardware and software that generated the model, and capture any modifications to the data.

Spatial/coverage/location metadata that supports GPS-based visualization on maps is another useful feature for documenting the location and geographic context of cultural heritage artifacts and sites, as well as the distribution of biological specimens. Multi-resolution streaming would be useful for visualizing 3D models with the level of detail needed. An open API would allow researchers better access for conducting independent analyses on open data. 3D models would better support re-use and long-term documentation if the access platform included tools that allowed users to independently make measurements on 3D models, and compare them with each other. One participant pointed out that X3D has a Geospatial component that facilitates double precision (lat/long) and different geodetic projections.

When asked to identify the features desirable in a platform for 3D model delivery, one participant quipped, "Everything that the Smithsonian 3D viewer has, but open source." While perhaps flippant, this comment nicely summarized and encapsulated the discussion. In brief, three main functions seemed to emerge from the discussion as the most desirable traits for a 3D model hosting platform: 1) Archiving and preservation of the digital files; 2) A viewer that is not tied to a commercial vendor platform for hosting derivatives; and 3) A decentralized 3D embeddable viewer clearinghouse or aggregator. In addition, participants clearly wanted advanced functions that allow searching based on shapes and other visual elements (Doerr et al., 2010; Lew, Sebe, Djeraba and Jain, 2006; Tangelder and Veltkamp, 2004).

## Integrating 3D Data into the Research and Scholarly Communication Environment

For this session, participants were asked to form groups based on their job type. Researchers sat with researchers, librarians sat with librarians, and commercial vendors and non-profit service providers were in a group together. The researcher group was asked questions about data archiving and representation, licensing, and cultural protocols based on tribal ownership. Librarians were asked about library programs designed to support research efforts with 3D data. Non-profit professionals and commercial vendors answered questions about hardware/software support and training.

### Scholarly publishing perspective

The researchers, when asked whether data should be published and preserved by a journal or by a repository, stated that, ideally, a journal should enforce peer review not just of publications but also of the research data. However, the consensus was that their fields are not at a point where the visual information contained in a 3D model is required to support the arguments and findings posited in a journal article. 3D data visualization and analysis on this scale in fields like architecture, archaeology, and even morphology is still very much a niche sub-discipline that most journal editors would be challenged to find reviewers who even understand the research data on the level required for rigorous peer review. The peer review of such data is challenging because it requires familiarity with both the field and the data type. A researcher who is familiar with the data type but not the field of inquiry might be able to determine if the measurements in the model are accurate and yet not be able to evaluate whether the model and its data support the findings in the publication. A peer reviewer could be one of the most respected researchers in the discipline but not know the data type.

Therefore, the researchers were not sure that peer-reviewers would be capable of analyzing the 3D models that support the findings in their articles.

Participants who conducted research based in 3D data believed that the 3D model is a scholarly work in itself. It needs its own DOI and citation because if it is viewed as an illustration or supplementary material, it will not be indexed in Google Scholar or similar engines. This introduces DOI granularity as an issue. For example, if each model has a DOI, there could be one hundred DOIs listed to support one article. Alternatively, a collection of one hundred 3D models that all support one paper could be treated as one dataset with one DOI.

A separate challenge is that some people see 3D models as merely illustrative as opposed to integral to the research findings and assertions. For example, one researcher mentioned a publisher that announced plans to launch a new journal to support 3D models and review. When it came to submitting articles and data, however, authors were instructed to put the models in Sketchfab, which is useful for illustrating models but not for analyzing them as a product of research in a scholarly journal. One participant researcher noted that some people have explored the idea of embedding 3D models within a document but warned that this would create accessibility and usability problems.

The researchers also discussed licensing. Several were surprised to learn that highly accurate representative models are expressions of facts and are therefore not protected by copyright. Access, however, can be controlled through licensing, contracts, and service agreements.[16] Most participants spoke favorably about open data. One indicated that his field was rather lonely, so he used open data is his strategy for expanding the scholarly conversation and boosting the impact of his work.

### Cultural heritage sector perspective

Participants from non-profit cultural heritage firms addressed the question of educational 3D content and roadblocks with licensing and cultural protocols. They described the state of licensing and cultural protocol restrictions as "evolving" but then noted that tensions sometimes arise between institutional units and their imperatives. On the one hand, the Smithsonian is obligated to protect the cultural artifacts of certain indigenous groups and limit the usage of some artifacts in accordance with tribal customs. On the other hand, the Smithsonian's mission is the "increase and diffusion of knowledge." In practice, this can result in agreements where certain materials can be replicated through 3D printing but may not be represented in a virtual environment. The participants see such a negotiated space as beneficial progress in the bicultural co-curation of digital material (Basu, 2013). Cultural protocols define certain allowable restrictions, but this is also an evolving area. Based on the complicated nature of negotiating this space, participants working in the cultural heritage arena emphasized the importance of bringing indigenous communities into the conversation at the beginning (before a project proposal is drafted, for example) rather than as an afterthought. Sometimes there are compromises, such as a site where external spaces, but not internal spaces, may be photographed. Furthermore, as tribal leadership sometimes changes, new leadership may revoke permissions, which then requires already collected image data to be destroyed. There is hope that combinations of technologies, such as the Mukurtu platform along with 3D modeling, might better enable digital repatriation by making cultural heritage materials available in digital format to members of the originating culture.

16 This part of the conversation referenced a presentation by Kyle Courtney of Harvard University at the CS3DP forum at the University Libraries of Washington University in St. Louis, January 2018.

A separate issue arises in 3D photogrammetry of sites or spaces that have been destroyed due to natural forces (e.g., Old Man of the Mountain in New Hampshire), or through conflict (e.g., Buddhas of Bamiyan in Afghanistan, or the Syrian Ruins at Palmyra)[17]. Visitors have repeatedly photographed such sites over the years – from multiple angles, depths of field, and lighting conditions – resulting in useful datasets for photogrammetry. Such collective crowd-sourced works result in models that have great value but rather uncertain provenance of ownership and rights[18], especially if there are conflicting rights statements associated with the source materials. Participants noted that U.S. and international laws lag behind the technology, resulting in a poorly defined and poorly understood legal environment.

### Librarian perspective

Librarians discussed the role that libraries can play in supporting scholarly uses of 3D data models. There was general agreement that libraries should support 3D data creation and archiving, particularly in the areas of providing sustainable archival infrastructure, managing metadata, and providing access to tools and research support.

Challenges facing libraries working to provide sustainable archival infrastructure include possible resistance from researchers to deposit their data (a common problem with other types of data) and the portability of data when researchers change institutions. One theme that emerged in this conversation was the need for cross-institutional repositories, which would benefit from adherence to standards such as X3D, a protocol that has been endorsed by the UK National Archives[19] as well as the US National Archives[20]. One participant pointed out that storage of data can be separate from things like metadata, unique identifiers, and discovery interfaces. Another participant suggested that 3D data should be integrated into existing initiatives in libraries to develop open access publishing programs. There was a general consensus that, by providing access to sustainable archival infrastructure, libraries could establish a leadership position in 3D/VR data creation and curation. Libraries need to work together to link currently disconnected silos and manage a constantly changing technological and scholarly environment. Libraries are well positioned to track scholarly techniques in rapidly changing academic fields, while simultaneously managing the migration of data when older systems and formats are threatened by obsolescence.

Because of their long track record in knowledge organization, participants also saw libraries as potential leaders in developing metadata standards and managing the metadata throughout the 3D data lifecycle. Libraries can help with basic data management tasks, such as issuing persistent identifiers and affiliation identifiers for 3D datasets. Participants stressed the need for libraries to work in concert to establish common standards and consolidate metadata collections for 3D data. Such collaborative work could take the form of an open 3D model archiving system, which would define file formats and establish uniform ways of archiving 3D files. Participants stressed that libraries are in a perfect position to establish uniform methods of archiving 3D files and

17 The Arc/k Project: Building a virtual archive to keep the Palmyras of this world alive: https://www.thenational.ae/arts-culture/the-arc-k-project-building-a-virtual-archive-to-keep-the-palmyras-of-this-world-alive-1.721436

18 National Public Radio Science: 3D Scans help preserve history, but who should own them? https://www.npr.org/sections/alltechconsidered/2018/05/21/609084578/3d-scans-help-preserve-history-but-who-should-own-them

19 UK National Archives PRONOM Technical Registry Details for X3D 3.2: http://www.nationalarchives.gov.uk/PRONOM/fmt/581

20 US National Archives Appendix of File Formats: https://www.archives.gov/records-mgmt/policy/transfer-guidance-tables.html

to make recommendations for research outputs appropriate for archiving (recommendations the CS3DP project is working towards). Some participants felt that establishing archival collection acceptance standards seems like a reasonable strategy given the difficulty in controlling how researchers create, analyze, and manage 3D models. Another participant cautioned that libraries should take a wait-and-see attitude, because it may be too soon to choose which 3D formats are the most appropriate preservation standards.

Librarians also discussed how best to provide tools and support for researchers creating 3D models. Participants noted that to encourage use of open standards for 3D data, better open source tools are needed. Researchers strongly prefer to use commercial tools for 3D model creation, which can obscure modeling and texturing algorithms, thus inhibiting scientific replicability. There was further discussion of the role of libraries in developing open source 3D creation tools, but the participants in this group acknowledged that there is already much competition among commercial vendors with sizable budgets making it unlikely that libraries can compete. One participant was not as sure about the level of expertise that could be expected from libraries with the technology environment for 3D creation changing so rapidly and felt it was important to avoid a situation of the "blind leading the blind." Output recommendations from libraries seemed more feasible than trying to control creation methods. Another major area of discussion focused on the importance of early engagement between researchers and library personnel to establish effective curatorial practices when creating 3D models. This early engagement would allow libraries to encourage best practices for data gathering, good documentation, and use of archival formats. Finally, participants thought libraries could support the work of researchers in producing 3D data sets by identifying ways to automate data creation from available tools.

### Vendor and trainer perspective

Commercial vendors and trainers addressed the question of using hardware and software to support metadata, replicability, and reproducibility. They recognized the importance of technology support for 3D integration into the research and scholarly communication environment. Two major themes surfaced from the discussion. The first was training. Participants communicated various ways to support technology training needs. While in-person training is one option, what about remote training? One option for remote training would be to create a VR experience that highlights best practices and demonstrates pitfalls and solutions to achieve better output. While it is customary for vendors to provide training, this group felt that they too would benefit from training that comes from the researcher's perspective. The vendor/trainer could shadow the researcher to learn more about their needs and practices, thus gaining a better understanding of how customers use their technology. A participant of the group mentioned that, while his company has cultural heritage customers, he is barely visible to those actually doing the work. He would like to see more vendor/customer interaction.

As researchers seek the ability to reproduce and replicate the files they are creating, vendors should be able to support the ability to replicate, although they acknowledged that the variability of 3D technology is an issue. Each 3D system has limitations and output varies. They welcomed the opportunity to work directly with their customers to determine needs and find the system that would best support the collections that need to be captured. The requirements of scholars must be specified and articulated to vendors as early as possible at the procurement stage.

In summary, these discussions revealed more ways that standardization can help the use of 3D digital objects in scholarly publications and as research data sets. Integral to making any of that data available, though, is the need for metadata to describe these 3D digital objects within the contexts they are being shown. The forum agenda discussion took on this topic next.

## Metadata Requirements for 3D Models

Rather than trying to invent a new standard, or reinvent something that already exists, forum participants believed that it would be most effective to consider 3D-specific metadata in the context of researcher needs and broader use cases (such as discovery and non-research access), and then map established metadata schemas, ontologies, and data models to those use cases. Researcher needs identified by the participants largely depend on an understanding of the trustworthiness of the metadata, the source and quality of the documentation, the technical information regarding the modality of the 3D model, and a defined relationship between 3D models and the specific objects from which the models are derived. Delving into the details of the metadata fields that satisfy these needs led participants to conclude that they were trying to define a standard that does not yet exist. The metadata elements described below show how a pre-existing metadata schema could map to 3D-specific metadata if a new metadata schema, ontology, or data model were created.

There are other use cases for which the best level of representation is not the virtual model or virtual environment but should instead be some feature of the model or environment, such as a particular texture, or shape. The W3C standard for media fragments[21] might provide a framework for achieving this, but so far it has only been applied to audio and video files (temporal media fragment) and there is no way of doing this yet for 3D model and scene files by ID, temporal, or spatial query.

For more general access purposes, existing schemas like the W3C Web Annotation Data Model[22], CIDOC-CRM[23] and models such as those used with Europeana[24] seemed to satisfy the needs that participants identified, including topic searching, aggregated collection searching, "type of thing" searching, and the FAIR concept – findable, accessible, interoperable, and reusable.[25]

Participants identified some necessary elements to document in metadata for 3D models. Several elements are already available in PREMIS[26], such as Method of Digitization, Capture Hardware, Processing Software, and Post-Processing Software. Some elements are in simple Dublin Core and other basic schemas. These elements include Title, Date, Rights, and License. Participants agreed that using rightsstatement.org was the simplest route to express Rights metadata for 3D models and data.

A digital object identifier (DOI) or other unique, persistent, citable identifier is also important, as is a relation field with a pre-existing unique identifier for the associated physical object. It is clear that the elements and fields mentioned so far already exist in metadata schemas widely used by libraries. Participants also found some more unusual fields specific to 3D modeling to be important: Size, Scale, and Modifications. Size and

21 W3C Media Fragments URI 1.0 Specification: https://www.w3.org/TR/media-frags
22 W3C Web Annotation Data Model: https://www.w3.org/TR/annotation-model/
23 CIDOC-CRM: Conceptual Reference Model: http://www.cidoc-crm.org/
24 Europeana: https://www.europeana.eu/portal/en
25 FORCE11: The FAIR Data Principles: https://www.force11.org/group/fairgroup/fairprinciples
26 PREMIS – Preservation Metadata Maintenance Activity: https://www.loc.gov/standards/premis/

Scale fields could be slightly more challenging to execute and standardize due to various units of measurement, as well as varieties of ways that size is measured (e.g., area vs. volume). Modifications (changes made beyond initial production) may be the most specialized and difficult field with the least amount of pre-existing guidance.

For digital repository metadata, more guidance may be required to define a Resource Type to encompass 3D and enable interactions that respect 3D. While "Model" is a pre-existing Internet Media (MIME) Type that already applies to the X3D standard, the DCMITYPE vocabulary only has labels such as Image and Interactive Resource.[27] The definitions for these labels, and the ways that these labels and definitions are applied in practice at institutions, may vary when it comes to 3D models.

To summarize the findings in this session, metadata requirements for 3D modeling should expand upon base metadata for researcher needs and document technical information, as well as scientific specimen or cultural heritage information. X3D can be a guide because it already supports a variety of 3D-specific metadata. Finally, the CS3DP Project (Moore, Skates Kettler and Rountrey, 2018) and the Smithsonian Digitization Program Office[28] are concurrently working in this area so new recommendations may emerge from that work by the time this paper is published.

# Conclusions

Among the findings described above, there are several emergent themes. One is a set of challenges around the future of 3D visualization technologies. The first challenge is the need to develop discipline-specific metadata models and data dictionaries for 3D research, as well as aggregation tools for expanding discovery. Another is the need for a universal viewer that can stream various 3D file types in a web browser. Finally, many participants were surprised to learn of the existence of an open ISO standard format for 3D files which is appropriate for preservation. This revelation shows the need for greater awareness of preservation and curation practices among researchers who work with 3D data.

Participants were universally interested in expanding broader discoverability along FAIR principles. More work is needed to standardize some elements of 3D model metadata and establish best practices based on emerging standards from diverse disciplines.

Participants expressed the need for an IIIF-like universal viewer that supports streaming and annotation on 3D models and makes archival master files accessible, while also serving derivative files based on user requirements. Participants felt that X3D was a preferable master file in such cases because, while OBJ is more widely used, it is not actively maintained, whereas X3D evolves through development by an international community. Because of OBJ's lack of active development and maintenance, it will never have new features and is further limited by the fact that, unlike X3D, it does not support embedded metadata.

Another major theme of the forum is that librarians involved in digital object management, as well as researchers, want to see better documentation for image capture and modeling processes in order to support replicability of research, reproducibility of models, and transparency of scientific process. It is worth noting that one of the industry representatives expressed amazement at the level of detail in data transparency required

27 DCMI Type Vocabulary: http://dublincore.org/documents/dcmi-terms/#section-7

28 Smithsonian Institution Digitization Program Office: https://dpo.si.edu/blog/scaling-3d-digitization-smithsonian

by researchers and librarians. He remarked that while this assembly had a higher standard of documentation and transparency than just about any other community he had seen, including the quality control groups in his software and hardware design teams, his firm could update the software to generate a report to include the level and breadth of detail necessary.

Finally, participants expressed a need for federated search or some other form of metadata aggregation, like DPLA or Europeana, that supports 3D collections in order to break down silos between disciplines. The requirements of an aggregator include a known structure and may require new discovery interfaces and dashboards. Alternatively, some participants believed an API standard could facilitate these activities. Standardization of structure and metadata were again highlighted as a priority for 3D/VR models and data sets.

The first LIB3DVR forum produced valuable insights for 3D creation and reuse, as well as ideas for bringing the 3D/VR community together. The forum also provided possible ways for the library community to support and help standardize the creation and publication of 3D models and their data sets across disciplines. The subsequent LIB3DVR forums focused on 3D/VR visualization and analysis, and repository practices and standards, respectively. The overall goal of the forums together is to produce findings to guide libraries into supporting workflows for 3D/VR production, use, storage, and preservation.

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