# Accessing 3D Data

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Chapter 6

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## ABSTRACT

*The issue of access and discoverability is not simply a matter of permissions and availability. To identify, locate, retrieve, and reuse 3D materials requires consideration of a multiplicity of content types, as well as community and financial investment to resolve challenges related to* ***usability****, interoperability, sustainability, and equity. This chapter will cover* ***modes****, audiences, assets and decision points, technology requirements, and limitations impacting access, as well as providing recommendations for next steps.*

## Introduction

3D digital data **preservation** and access are complex and multilayered, involving many variables, including standards, best practices, open-source versus proprietary software, migration, and versioning. While 3D models hosted on platforms such as Sketchfab can sometimes (if downloadable with a compatible format) be reused for visualization, they are typically decimated models that are not acceptable for analysis. Other high-**resolution** models that can be downloaded are a step in the right direction; however, they typically require requested access (e.g., CyArk) or are difficult to download on lower bandwidths. As for scholarly reuse and peer review, most academics must not only be able to access 3D data, including raw, derived, and scene data, but they also need included critical **metadata** and **paradata**.[1]

When considering access to 3D materials, it helps to define what is meant by access. We are talking about the means to discover, examine, retrieve, or reuse 3D materials—because the issues of access are not simply a matter of permissions and availability. For example, to reference an audience use case that is discussed in depth later in the chapter, a researcher is attempting to study coral reefs, but some 3D models are **point clouds**, some are **meshes**, and some seem not to be scaled. For trusted reuse of data, the **provenance**, capture data, and apparatus surrounding the final product are essential in building a case using 3D materials from multiple sources. To do so requires consideration of (1) different modes of content type, (2) the needs of different audiences, (3) discoverability, (4) an understanding of technological requirements and limitations, (5) accessibility and inclusivity concerns, (6) the need for community and financial investment, and (7) citability guidelines.

In terms of 3D materials, following standards and best practices that promote interoperability is a viable strategy for ensuring long-term preservation and access of 3D content because they enable reuse of this material across any number of open-source or commercial software applications. Audience scenarios are used to explore the motivation for the use of 3D content by different audience categories. These scenarios emphasize the ways users discover 3D data and how each audience is using those data. In addition, the scenarios are used to evaluate technology needs and constraints as well as considerations surrounding accessibility and inclusivity for the widest set of audience categories. This chapter concludes with an examination of challenges to 3D data access, from discoverability, to use and reuse, to the creation of international standards, and to use of this work in promotion and tenure. Suggested next steps include possible repository solutions, methods to insure interoperability, uses of metadata in access, furthering accessibility and inclusivity, and evolving annotations, standards for peer review, and formats for citing 3D work.

# Modes of 3D Data

While the bulk of this volume deals with scanned or photogrammetric reality-based models, 3D work can be made available in many forms, from simple CAD models to fully fledged virtual environments. Nine modes have been identified and examined in the appendix, and this chapter draws upon the diversity of modes when considering the matrix of issues surrounding access. Whether proprietary software impacts the interusability of data or virtual machines are necessary to fully resurrect a virtual environment, each presents challenges from creation to access to preservation. The appendix attempts to deal with the issues surrounding each phase so that creators, users, and archivists (among others) can make informed decisions.*

* Tables in the appendix describe each of these modes, detailing source material, methods associated with capture, hardware and software needed for capture and creation, output format, derivatives, methods of interaction, minimum files needed for access, and maximum files needed for preservation.

# Audiences for 3D Data

Good discoverability and access practices begin with understanding the audiences that need to be served. When creating 3D material, institutions and organizations are likely to have established expectations regarding the end use of their content. While the end use of content may be known and is often a driving factor for the generation of 3D material, how the content might be reused in the future is often unknown or an afterthought. A natural history museum, for example, may digitize collections for its own preservation and management purposes, but it is also responsive to the communities it serves; thus, the needs of secondary users critically shape consideration of access and **discovery**. A project such as UMORF (University of Michigan Online Repository of Fossils) provides students, faculty, researchers, and a general audience with a collection of online 3D and 2D fossils from the University of Michigan Museum of Paleontology that can be examined within an online viewer. Designed with these audiences in mind, UMORF contains functionalities that allow users to spin the specimen, zoom in closely to see details and textures, toggle measurements on and off, and even see the object in anaglyph or interlaced 3D. Additionally, the hosting platform is rich with contextual metadata that supplement the visuals. These functionalities enable a wide range of information that can be useful to various audience types.

The following discussion explores how 3D material appeals to a multitude of audiences and defines the six main audience categories that are likely to need access to 3D data and related materials.[2] These categories may be porous but should help to identify what is at stake, of value, and important to users looking to employ 3D content. To further emphasize these perspectives, fictional scenarios are presented as exemplative use cases to demonstrate the particular wants and requirements for the specific audiences described.[3] These examples and scenarios presume noncommercial uses for the 3D content and a share-and-share-alike stance toward distribution. For-profit commercial and professional uses that might require licensing or use fees and rights and reproduction agreements are beyond the scale and scope of this chapter.

## Audience Categories

### Scholars and Researchers

The category of scholars and researchers refers to academics investigating 3D work or utilizing 3D methods for an evidence-based understanding of design and the development of new knowledge and learning opportunities for the public in formal and informal environments. They should have a knowledge of 3D methods that reinforces their use of 3D data for research.

Scenario: An art historian wants to interact with another scholar's sources-based reconstruction of an ancient site in order to test her own theory regarding the quality of light on a wall painting.

Scenario: A research team has scanned the underwater topography of a reef in Mexico and wants to combine it with similar datasets. They are equally happy working with point clouds or 3D meshes.

### *Educators*

Educators in this context are defined as all instructors working with learners across all age and ability levels. These educators will likely have specific needs based on their students and use the 3D material to advance their own knowledge or incorporate into their pedagogy. Access will depend on whether the available 3D content meets their specific learning objectives or matches with their lesson plans and standards (state and federal). Additionally, access for educators is usually contingent on device availability.

Scenario: A high school teacher wants to teach a class on research methods by having her students reconstruct buildings from Victorian London using a free computer modeling program and so wants to locate existing academically generated models for a classroom discussion at the start of the semester.

### *Students*

Depending on their age and abilities, students will have different sets of expectations and goals for seeking out and interacting with 3D materials. They may be interested in learning more about the content the model represents or the technical processes that are involved in producing 3D data and objects and what they can communicate regarding the physical objects or terrains themselves.

Scenario: Undergraduates in an American studies class are searching for 3D models of Native American pottery. Their assignment is to identify recurring decorative patterns and analyze them across cultures. If there is not a shared repository for such materials or connections among **archives**, this would require them to access multiple archives. The instructor may or may not provide them with links to known websites with Indigenous materials.

### *Museums, Public Outreach, and Nongovernmental Organizations (NGOs)*

Institutions with missions to offer learning opportunities for the public via alternative environments may seek out 3D materials to supplement or support their existing programs and resources. Their motivation is to provide multiple pathways for broadening access to and engagement in learning experiences. For museums specifically, 3D materials enable display of resources that are warehoused due to lack of space and minimize handling of irreplaceable specimens. Virtual models also offer a way to present material that could not be displayed in a museum space, such as a reconstruction of a city's built landscape. Additionally, museums often turn to 3D models to facilitate user interaction and engagement with objects printed from 3D files. This is particularly important for museums that wish to serve those who are visually impaired. 3D printed objects can increase access and allow for haptic learning.

Scenario: A museum wants to 3D print bones from the skeleton of an endangered species as part of a hands-on installation for kids.

### *Professionals*

Covering a wide range of expertise, the professionals category includes artists, architects, medical practitioners, engineers, game designers, animators, and more. These users avail themselves of 3D tools and content regularly within the scope of their work. The needs of the users encompassed within this category can vary greatly, which makes it a difficult category to address. Because this group potentially has commercial interests in the 3D content, they will be interested in intellectual property rights, licensing, technical specifications, and issues surrounding monetization (see chapter 5, "Copyright and Legal Issues Surrounding 3D Data").

Scenario: A mixed-media artist wants to build virtual experiences that incorporate scanned statues from museums across the United States to explore questions of scale and gender identity.

### *General User/Personal Interest*

A general user would be described as anyone interested in material that is presented in a 3D format. The person could be any age or background with undetermined preknowledge. Their needs and expectations could vary widely, but they will likely be looking for a ready-to-use 3D experience that aligns with their personal interests and available technology. Intuitive features are very important to general users.

Scenario: A history enthusiast has just finished reading a book about the Gilded Age in the United States and wants to explore academically generated 3D environments that can immerse him in the time period. While he has some basic knowledge of the era and its architecture, it is critical that these 3D reconstructed environments be fully annotated in order to provide a general user an edifying experience.

## Discovering 3D Assets and Decision-Making Issues

Discovery methods for 3D materials and related resources are crucial and also fragmented. At present there is no one unified way to find 3D assets, although some disciplinary silos have begun to occur and may provide a way forward for discovery depending on a user's needs. Currently, finding all 3D cultural heritage materials, even for a given location, can be difficult as different digitizers may have mounted their materials on different platforms. Similarly, libraries don't have a standard way of referencing these data, and it is often difficult to determine what a given institution's 3D holdings are.

Because needs can vary among the six audience categories based on their search experiences, parameters, and goals, we have articulated in table 6.1 the most common ways of finding 3D content and to illustrate the complexity of discovery.

**TABLE 6.1**

The most common ways of finding 3D content

| Discovery Method | Explanation |
|---|---|
| Web search engines | A web search for "3D models" usually directs users to proprietary online repositories that are designed around consumer-based models; examples include sites like Sketchfab, TurboSquid, and CGtrader. |
| Online repositories | While proprietary online repositories can be found through web search engines, there are many libraries, archives, and museums that are working to create access for 3D materials online. |
| Searchable meta-data | If 3D objects are shared with searchable metadata, audiences may be directed to them when a user searches for a specific type of object, location, title, creator, etc. |
| Word-of-mouth | While 3D is a growing community, many still hear about new content through personal channels. |
| Classroom exposure | Students often learn how to use 3D content and where to find relevant 3D materials during particular classes in their respective disciplines. |
| Professional training | Vocations like architecture or animation often require specialized training in particular 3D modeling techniques and software, and in the course of that training, students and professionals alike are directed to known caches of relevant 3D material. |
| Entertainment | The general public has exposure to 3D material through popular entertainment like 3D films, virtual reality, and video game play. This exposure may spark a search for 3D content that employs one or more of the above methods. |

Once material has been discovered, certain conditions play a critical role in the use and reuse of 3D materials, and many of them inform the development of infrastructure and metadata schemata. Four out of the six audience categories (scholars and researchers; educators; students; museums, public outreach, and NGOs) will likely share common concerns regarding academic rigor of the project. However, professionals and general audiences may not find all of the concerns in table 6.2 to be of interest.

**TABLE 6.2**
Common concerns about 3D data.

| Need | Explanation |
|---|---|
| Digital literacy | Provide 3D content in a way that is accessible to a given audience allowing users to successfully engage with and evaluate 3D content. |
| Ease/availability | The 3D material is discoverable and accessible, and the audience is able to reuse the content in a way that suits their goals for engaging with the material. Also, 3D content is provided in a way (such a web-based viewer and a smaller sized dataset) that requires the least specialized hardware and software. |
| Trust | It is readily apparent that the models are accurate and truthful, and there is readily available information about the construction or generation of the models. |
| Ethics | It is apparent that the 3D materials were generated or created with appropriate permissions and acknowledgment of intellectual property, considerations regarding the use of the material (e.g., immersion in educational settings), and providing visible credit and citation for work produced. |
| Consistency | The models include metadata fields that are generated in accordance with accepted community standards. |
| Utility | Use of the models is justified by a basic return-on-investment calculation (i.e., the personal time required to locate a model and learn the necessary technologies for use can be justified by the benefit of the engagement). |
| Interoperability | The models can move easily across platforms as desired, and critical metadata can be transferred from the 3D models. |
| Accessibility | The models include accommodations for differently abled users. At the moment there is very little offered in terms of virtual 3D materials that make for suitable accommodations for visually impaired users.[a] This is not just an academic concern. It should be a concern for any user. |

a. For a more detailed discussion, see the document "Policies and Standards." https://www.hhs.gov/web/policies-and-standards/index.html

Additionally, two of the six main audience categories have specific concerns for decision-making issues regarding delivery systems for 3D materials. Educators will value classroom time, —available time in the classroom or within the lesson plan to integrate 3D materials—as well as the pedagogical return on investment for teaching and learning (i.e., Does the 3D material significantly outpace other forms of instructional technologies?). Professionals, on the other hand, have specific concerns that will vary across professions but could influence use or rejection of 3D materials. For instance, architects searching for 3D models to provide context for their own designs will have very specific requirements concerning rigor, dimensionality, and visual style.

The areas of focus listed in Table 6.2 should inform decisions made in terms of discovery and access. Most critical is that metadata developed for the 3D materials expose information to the users so that they can make informed decisions about the available content. At minimum, these metadata must include detailed information about the technical and academic pedigree of the material—information about the creation of the data and their reuse, the level of rigor and veracity used during their construction, and statements from the content creator about the project's objectives.

# Technology Requirements and Limitations Impacting Access

Moving beyond **source material** and capture, it is important for this chapter to consider *how* the data will be accessed. This chapter privileges the creator's intended use so as to limit scope. However, the technology required for interaction needs to be examined as different audiences have access to different kinds of technology. When considering all six audience categories, modes of access can vary greatly based on hardware and internet access.

For example, while in the United States, about 75% of American households have broadband internet service,[4] in Mexico in 2018, only 44.9 percent of households have a personal computer, and only 13.26 percent have fixed broadband subscriptions.[5] Even smartphones increase market penetration only to 56%.[6] Public libraries and internet cafés provide ways to get online, but many will not allow specialized software or large file sizes to be downloaded. Thus viewers that allow access over the internet provide a distinct advantage when considering access for the broadest category, the general public. A virtual world or environment or a model that needs to be accessed in high resolution to evaluate its integrity can be a permanent barrier to entry (see table 6.3).

**TABLE 6.3**

Good/Better/Best recommendations for online 3D data file types

| Tier | Recommendation | Examples |
|---|---|---|
| Good | Agnostic file type that is uploadable to a web viewer and loads relatively quickly or can be viewed with free or open-access desktop software | Final decimated model |
| Better | High-resolution files and access copy | High-resolution model available for download (when copyright allows) and final decimated model for web display |
| Best | Raw data, output files, high-resolution files, access copy | If the model was captured photogrammetrically, link to raw photographs or model as output from modeling software before cleaning, high-resolution model, final decimated model |

If access is the predominant concern across audiences, however, then web-based viewers such as Sketchfab will aim to accept the differing formats of these models and allow additional annotation. While at this writing Sketchfab is the most popular commercial software available, it is important to note that models hosted on Sketchfab are subject to size limits,* and while users retain ownership over their content, Sketchfab is a hosting solution, not a repository. Others are working on viewers that would be self-hosted, such as the Smithsonian's Voyager or 3DHOP from the Visual Computing Laboratory at the Istituto di Scienza e Tecnologie dell'Informazione.[7] A self-hosted viewer removes constraints on the size of the model (although many models need a decimated or optimized version for distribution so as to make loading times reasonable or to meet hardware constraints) and allows more control over generated data. That said, desktop applications such as MeshLab or CloudCompare for scanned and photography-based models are necessary if high-resolution versions of a model are available for detailed inspection, measurement, or comparison.[8] This is also where repositories such as MorphoSource come in, as they often provide high-quality models for download and inspection.[9]

# Use Case

Researchers at Indiana University investigated how differences in capture were reflected in resulting photogrammetric models.[10] They used several models from the Stanford 3D Repository that were scanned at high resolution and synthetically photographed the models in Blender before processing the results in PhotoScan to recreate the models.[11] These results were loaded into CloudCompare to determine best practices for capture and investigate tolerances, as seen in figure 6.1. This methodology could also be used to compare captures by different entities where scientific tolerances are important or artistic integrity of the object is paramount.†

* Sketchfab is currently prototyping streaming for "massive" models, but the feature has not been rolled out at the time of this writing. (Bart Veldhuizen, "Stream Massive 3D Models, Now with Texture Support," *Sketchfab Blog*, July 31, 2019, https://sketchfab.com/blogs/community/stream-massive-models-now-with-texture-support.)

† For example, there are two reconstructed versions of the Palmyran Arch of Triumph blown up by ISIS in 2015, one 3D printed by the Institute for Digital Archaeology (IDA) and an online model by The Arc/k Project (Arc/K). However, the online version is not downloadable, and the printed arch is patented with limited accessibility, both by the people whose cultural losses are meant to be represented and by those who would be educated in that loss. (Roshni Khunti, "The Problem with Printing Palmyra: Exploring the Ethics of Using 3D Printing Technology to Reconstruct Heritage," *Studies in Digital Heritage* 2, no. 1 [2018]: 1–12, https://doi.org/10.14434/sdh.v2i1.24590.)

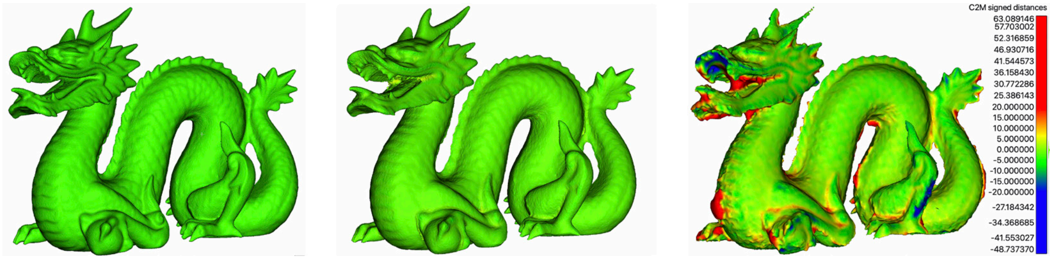


**Figure 6.1**
Using desktop applications to interrogate 3D models

For immersive worlds and virtual environments, there is no standardized access format at the time of this writing. The **emulation** strategies employed by the Internet Archive and championed by organizations such as the Video Game History Foundation are preserving the user experience of many classic computer games, but one-off academic projects and virtual models and environments are in danger of disappearing from the scholarly record.

# Challenges and Outstanding Questions

To facilitate and foster 3D data reuse, we must take into account the considerations mentioned in the appendix; however, four areas rise to the surface as the most critical: discoverability, interoperability, citability, and peer review. The following sections demonstrate how the ability to locate, use, evaluate, and reference 3D materials affects the audiences and technology requirements listed earlier in this chapter. Adding to the complexity of the topic of access, these four factors are interdependent. As a result, consideration of any one factor requires consideration of the others. The essential work being done within these areas will establish consensus regarding practitioner and archivist **workflows** and infrastructures for preservation and exchange.

## *Discoverability*

At the moment, there is no central repository for all 3D scholarship, even for the modes that can be gathered together. For example, DigiMorph.org (University of Texas) went live in 2002 to serve visualizations derived from high-resolution **X-ray computed tomography** (HRXCT); it was not, however, designed to serve the HRXCT data themselves. Since then, Duke University's MorphoSource has made inroads, as it is designed for **volumetric data** of biological and paleontological specimens with downloadable files ranging in format from the raw data (e.g., TIFF HRXCT slice stacks) to derivatives (e.g., .stl, .obj, .ply). This approach speaks to the possibility of separating 3D work by discipline rather than method of production. Cultural heritage work, for example, could be deposited into central repositories that would ideally allow options for both viewing and downloads.[12] 3D ICONS—a Europeana project focused on cultural heritage—does include appropriate metadata, but models are often not downloadable or cannot be viewed in an interactive 3D web display.[13] The integration of a viewer would be more important here, as rights restrictions come into play often with cultural objects, meaning that the raw dataset would never be available for download if intellectual property rights are not released. That said, further challenges occur when one moves beyond models to virtual worlds, environments, and games, each of which may necessitate specialty software for playback. These modes and their need for software (some of which might be proprietary) mean that not all end users may be able to access every piece of 3D work in a repository (if on a public library computer where software cannot be downloaded, for example).[14] However, if there were central repositories for 3D data, at least similarly cataloged work could be found—pointing to the need for robust and standardized metadata. Such repositories need not actually host all the work if rights management or scope of storage and management becomes an issue. Rather they could be **aggregators** with **persistent identifiers** linking out to work hosted elsewhere.

Some university libraries have begun hosting 3D content, but their metadata and cataloging strategies are not consistent. Some libraries refer to the method of digitization, and some simply call their material by the type of holding (e.g., OBJ, PLY). As a result, the major metadata aggregators such as WorldCat would need to incorporate additional parameters to successfully return comprehensive results. The first step toward finding available 3D content lies in standardized metadata surrounding each mode of 3D content.

In chapter 4, "Metadata Requirements for 3D Data," attention is given to how standardization of language plays into discoverability by non-3D practitioners, such as librarians who may be assisting patrons. One must also consider the role of verifiable provenance and tools for recreation (when rights permit) as well as evolving citation standards. In addition, each dataset requires a globally unique identifier (GUID), digital object identifier (DOI), or Archival Resource Key (ARK) if it is going to be findable by a catalog like WorldCat. Preferably, the identifier should be a globally unique persistent and resolvable identifier (GUPRI). Chapter 4 also rightly points out that a physical specimen may need multiple identifiers if different derivative or digitally constructed versions are available.

## Interoperability

Interoperability for 3D data remains a major challenge. Numerous file formats exist for proprietary software that often are not interchangeable—it is difficult to achieve interoperability without a legal framework surrounding both licensing and open-access data. Data types such as point clouds and meshes are based on ASCII, binary, or both. While ASCII is recommended for long-term archiving and is essentially interoperable, it does not necessarily facilitate access and reuse because it stores minimal metadata and lacks paradata. While no standards exist, common file formats for 3D models include OBJ, PLY, DAE, and STL, which can be used in many software packages, and this is where API converters could help bridge the gap between different file types. However, each of these formats has pros and cons, and file conversion for interoperability can change the initial raw data.

Virtual environments tend to be more complex because they are typically proprietary and often originate from multiple datasets, and the viewers required to interact with them include additional elements such as lighting, sound, and collision detection. Additionally, game engines such as Unity3D and Unreal Engine have numerous versions that are not backward compatible; that is, files created with newer versions cannot be opened in earlier versions. While many (but not all) older projects can be opened in newer versions, incompatibility between versions still exists requiring editing code to ensure original visualization and functionality. Based on open web standards, WebGL, along with 3D libraries and APIs such as three.js, provides an alternative for 3D visualization; few current software packages, however, are based on these open standards because they require intense coding by experts as well as consistent updates. Thus, while 3D visualization options exist (both proprietary and open-source) that are in theory interoperable, for example, they often do not have cross-compatible file formats, and the difficulties associated with migration and versioning are also often a roadblock. 3D analysis is a greater challenge because to carry out scholarly research requires having access to metadata and paradata. Additionally, it is critical that researchers have access to original 3D data (not simply derived models) to facilitate interoperability with other software as a single 3D visualization software is often insufficient for analytical purposes. As for CAD data, they are particularly challenging because not only are there numerous file types (extensions), but there are also many CAD-software-using native formats that are not interoperable.

3D data lack official standards, and this lack lessens their interoperability. While best practices and standards are slowly are emerging,[15] because of obsolete and diverse formats, versioning, specialized technologies, and rapid development of new software, there is no consensus on standards,[16] and it can be difficult to adhere even to recommendations.[17] For example, while OGC (Open Geospatial Consortium) highlights standards for some 3D formats, such as LAS, CityGML, and I3S, most of the commonly used formats, such as PLY, OBJ, and DAE, are not included. A key challenge for geospatial 3D data is that many 3D file formats cannot store or work with real-world coordinate information; thus, data integration is difficult. For example, DEMs and shapefiles lose their real-world reference in 3D gaming engines, which makes it difficult to easily ingest other georeferenced 3D models to create virtual worlds. To move forward with standards and best practices requires that communal work take place across disciplines and organizations to develop a set of 3D data standards that promote data exchange and interoperability for now and into the future.

Another major challenge for interoperability are the differences in 3D point clouds (acquired from **laser scanning**) versus 3D meshes comprised of faces (generated from 3D point clouds). While conversion from point clouds to meshes is commonplace, it is essential to realize the potential data loss and **transformation** from such conversion on the raw data. In other words, decisions are already being made that alter the data based on use purposes—public dissemination and research have different requirements.

Even if 3D data are interoperable and reusable for visualization, they are rarely reusable for scholarly purposes. While reality-based 3D models derived from **photogrammetry** and laser scanning can theoretically be reused, available models are typically decimated for web-based visualization. The decimation process sacrifices elements of the original data (e.g., geometry or **texture maps**) in exchange for viewing efficiency, resulting in data loss and potentially limiting the models' usefulness for secondary analysis because the optimized models no longer contain the original data that made them desirable to researchers in the first place. Models that are not optimized, however, are often too heavy for many computers to visualize or run computational analyses requiring both large amounts of RAM (memory) and processing power as well as expensive, powerful video cards (depending on 3D model mode). Reuse of 3D models and virtual environments created using 3D Studio Max, Maya, or AutoCAD, for example, is more complex, not simply because of proprietary formats, but also because of associated metadata and documentation. 3D reconstructions typically comprise multiple data sources such as GIS data, architectural drawings, photographs, field notes, and so on, and it is essential to know the data sources and modeling decisions (parameters) made in the reconstruction for scholarly reuse and peer review.[18] Similarly, 3D models and reconstructions that are repurposed mostly are not cited despite the scholarly work that goes into creating them.

## *Accessibility and Inclusivity*

Ideally, content creators would consider different audiences and delivery platforms as they develop their 3D work and tools so that the materials serve the widest possible array of audiences. For example, decimated versions of models can be made available in web delivery players with links to higher resolution models linked in the metadata. Providing two versions of the material enables both web interaction and more detailed and stable offline exploration. It is also worth considering inclusivity when discussing access to 3D data. At the time of this writing, while the World Wide Web Consortium (W3C) promotes its Web Content Accessibility Guidelines (WCAG), recommendations for making 3D material inclusive are just beginning to be discussed.[19] The issues of inclusion can be wide-ranging, assessing both access to and the quality of software, hardware, and internet connectivity. Inclusive practices also address concerns regarding differences in digital literacy and skill sets, economic situation, education, geographic location, language, age, and disability. For online content and digital tools, accessibility-compliant materials would allow users with disabilities to "perceive, understand, navigate, and interact" with websites and tools so that they "can contribute equally without barriers."[20]

A project that could inform this inclusivity discussion is the Project Gap Analysis Rubric developed by Jasmine Clark to help practitioners assess the extent to which a digital project is accessible, usable, and inclusive. Through seven layers of criteria, practitioners rate a total of twenty-one elements as Weak (1), Average (2), or Strong (3) and tally their results. Including specific and detailed project information will yield a gap analysis that will be both concrete and actionable. The rubric elements combine well with something like Francesca Albrezzi's XR Implementation Checklist as a way to think about accessibility, usability, and inclusion within the early stages of a project. Clark stresses that even if practitioners do not have the time or resources to accomplish everything within the rubric, considering such matters is a substantial step.[21]

In terms of digital publication platforms, the University of Michigan Press/Michigan Publishing's e-book platform Fulcrum acknowledges that accessibility is a core value of its user experience design, adhering to the latest WCAG Level 2 AA Standards and providing users information about known web accessibility issues.[22] Fulcrum was used to publish 3D content with its 2016 release of *A Mid-Republican House from Gabii*.[23] Again, Jasmine Clark has helped pave new ground for digital publication in terms of accessibility and inclusion by creating a VR Accessibility Resource Sheet and a Web Accessibility Primer.[24] These resources serve to better educate and assist web designers, students, librarians, and scholars on how to make their immersive technology endeavors meet current standards and to help differentiate between web accessibility, usability, and inclusivity.

## Annotation of 3D Research

Increasingly, academics assert that 3D models—particularly reconstruction models—can and should be seen as rigorous scholarly arguments in and of themselves.[25] Enabling that transformation from dataset to scholarly object requires the ability to associate the 3D models with supplemental information beyond the basic metadata required for discoverability. This supplemental information could be textual (e.g., spatially aware "footnotes" in 3D space that provide context, references to source material, paratext, explanations about interpretive decisions), expressed by the model itself (e.g., visual elements that signal areas of uncertainty, strategies for representing gaps in the available evidence, multiple reconstruction alternatives), or overlaid on the 3D model as a linear argument akin to the Tour feature built into the Sketchfab and Smithsonian 3D viewers or the Narrative feature in VSim.

When considering the infrastructure necessary to access and use 3D data, it is vital to consider the characteristics of the data. Depending on the domain of practice, the 3D data could represent a simple object, a large-scale virtual environment, or a complex spatiotemporal object that changes its morphology and its surface appearance in response to user interaction or changes in virtual world time. For example, several projects have proposed using photogrammetric models to monitor coral growth and die-off around the world, and the ability to compare models of the coral reefs generated over time will be critical to these efforts.[26] Similarly, Bernard Frischer uses computer-simulated shadows over time in his article on the Montecitorio Obelisk and the Ara Pacis to reveal "over 230 hitherto unrecognized solar and shadow alignments" to "create a recurrent sun and shadow spectacle that would have impressed the ancient viewer with [Augustus]'s learning, power, and religious commitment."[27]

Further confounding the requirements for reuse and preservation, 3D models themselves can also be considered as objects of study. Janet Delve describes them as complex and multimodal objects that are internally differentiated, hierarchical, and heterogeneous.* In this reframing, the model, as a scholarly object, is not merely the finished product as defined by the content creator, but an array of model iterations that illustrate its development over time. Thus, tools developed to support reuse and preservation must supports three functions:

- the display of the model's changing morphology over time,
- the display of the final and preceding versions of the model, and
- the display of the surface appearance of the model so that it symbolically represents one or more ontologies of data.

With respect to the last function, the 3D model plays a role akin to the 2D polygons used in geographic information systems (GIS). It can change its surface appearance from photorealistic to a symbolic color to show things such as the ethnicity of a given building's inhabitants, the provenance of a given tool's manufacture, or the reliability of a given building component's reconstruction.[28] Given this radically different conceptualization of 3D models as knowledge constructs, it will be crucial to devise new expressive, attestive, and workflow conventions that support the critical apparatus

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* Janet Delve explains, "An essential first step when considering the nature of complex digital objects is to recognize that there are multiple layers of difficulty encountered when attempting to analyse them. These layers could be superficially likened to Georg Cantor's 'levels of infinity' in terms of mapping out the size of the problem space to be analysed. The first 'level of infinity' is that of detail: the problem of drilling down through many layers of technical elements, showing levels of interconnectedness both within digital objects themselves, and also with their technical environments." (Janet Delve, "Introduction to POCOS E-book 1: Preserving Visualisations and Simulations," in The Preservation of Complex Objects, ed. Janet Delve, David Anderson, Milena Dobreva, Drew Baker, Clive Billenness, and Leo Konstantelos [Portsmouth, UK: University of Portsmouth, 2012]: 10–11.)

surrounding digital scholarship and provide for citability of models and environments in different states.*

## Citability and Peer Review

As mentioned above, citability and peer review are critical to encouraging scholars to make 3D data accessible and to reuse 3D data for academic scholarship. To enable the citation of 3D data by secondary scholars requires developing standards and best practices for referencing 3D scholarship. Because 3D data encompass geometry, metadata (publication and bibliographic), and paradata, citation is not straightforward. The use of open standards for file types and best practices for exporting and importing 3D data from multiple platforms can facilitate and foster broader publication and thus expand opportunities for discovering, using, and citing 3D material. Exporting 3D models and scenes using (still emerging) standards would allow them to more easily be reused as originally intended (without modification) for visualization and explanatory purposes in scholarly arguments because users could employ open-source, rather than only proprietary software to interact with and peer-review both models and arguments made with the models.

One way to approach the challenge of data structure is to develop and publish workflows or develop tools, such as the Digital Lab Notebook by Cultural Heritage Imaging (CHI), that provide guidance and easy-to-implement tools for documenting models using ISO-standard-compliant metadata to standardize and package geometry and metadata.[29] Providing workflows that offer step-by-step guidelines of best practices is a critical step toward creating citable 3D models that can be peer-reviewed and reused for new scholarly research. However, because of a lack of standards and infrastructure, it is still a challenge to carry original model attribution and metadata across many generations of derived models, thus inhibiting citation even when original models are properly cited.[30]

Moreover, as discussed above, web-accessible citation formats—using machine-readable formats that are "fixed to a specific file or bundle of files over the lifetime of those objects, even if their location on the internet changes"[31]—need to be employed for 3D models to allow them to be discovered and cited. For example, the Virtual Hampson Museum, with a specific focus on reusing and repurposing 3D models, hosts 3D objects. Originally each model had a URI and was downloadable.[32] However, because of

* Building information modeling (BIM) allows professionals to annotate and track data within virtual structures during their development and throughout their life cycle. By adding new metadata fields, scholars can adapt the schema for research documentation purposes. However, some, like Susan Schreibman and Costas Papadopoulos, are considering the efforts that are needed to produce a digital scholarly edition with 3D content. (Costas Papadopoulos and Susan Schreibman, "Towards 3D Scholarly Editions: The Battle of Mount Street Bridge," *Digital Humanities Quarterly* 13, no.1 [2019], http://www.digitalhumanities.org/dhq/vol/13/1/000415/000415.html.)

misuse of Creative Commons licensing, the models are now available only via 3DHOP and no longer downloadable, thus introducing another roadblock to reuse.

As for infrastructure, a few options exist for 3D publication. Journals such as *Digital Applications in Archaeology and Cultural Heritage* allow simple, low-resolution (typically decimated) models, or *Studies in Digital Heritage*, interactive 3D scenes (using Unity 3D–based platforms) to be included with traditional text. Recently, publishers have been experimenting with digital books with interactive 3D models linked to a database to allow data queries of model attributes (descriptive data) that form part of the scholarly argument. VSim, while developed for pedagogical purposes, also offers a way to reuse existing models to construct scholarly arguments that could potentially be used for peer review; however, as a desktop application, it must be downloaded for use.

# Recommendations for Next Steps

Given these critical challenges, the following recommendations provide actionable interventions for the 3D community. In response to the previous challenges, these areas have been identified as opportunities for strategic development to improve the quality of access for 3D material.

## *Develop Repository Solutions for 3D Materials*

While there are notable commercial repositories, the 3D community is primed for an aggregated repository or portal that would allow many 3D archives to be searched at once. An undertaking such as this would likely require the founding of a consortium, which would act in accordance and collaboration with others like IIIF, W3C, International Internet Preservation Consortium, and the Software Preservation Group. More than one such repository may need to be established in order to address particularities regarding content type and discipline-specific needs. To support these efforts, strong standards would need to be formed around linked open data (LOD) to take full advantage of 3D initiatives. Additionally, this work should establish a mechanism to include 3D materials in WorldCat and similar systems so added 3D objects have an appropriate level of inclusion in search aggregators but do not overwhelm the user or the platform.

The standard 3D metadata schema should also be expanded to include optional fields that enable Geoweb (i.e., finding all assets for a region simply by drawing a box and having 3D assets come up).[33] At a minimum, this would require latitude, longitude, and altitude for 3D assets. For even greater searching, the element of time could be added with date ranges. While Geoweb 3D work of this nature raises issues that would need to be addressed with sensitive site locations, the workflow could allow 3D data to cross disciplines and solve many problems of discovery that currently exist. In this case, the metadata would use geographic location as a standard feature.

## *Enhance Interoperability*

While the hardware and software involved in producing a 3D model may be specific, interoperability standards could allow different 3D data types to be shared across various viewers. The IIIF 3D community group is currently assessing features of available viewers to identify common requirements and map the landscape of available options for cultural heritage content. Goals are

- To explore possibilities for viewing, search, discovery, and annotating 3D data.
- To collect and document use cases from existing and new IIIF community members that suggest the need for interoperability of 3D data.
- To collect, discuss, and evaluate the state of the art with respect to 3D requirements for use by the cultural heritage community on the web.
- To coordinate and connect through outreach to internal and external partners, technical experts, and related initiatives.
- To explore best practices for interoperability and possibilities with existing IIIF specifications and open APIs through articulating use cases and experimentation.[34]

## *Employ Standard Metadata and Cataloging Schemata*

Agreed-upon metadata standards should be employed wherever possible, and the table of best practices in chapter 4 of this book, "Metadata Requirements for 3D Data," should be employed, as well as looking toward the use of RDF and OWL as described below in Table 6.4.

## *Design for Accessibility and Inclusivity*

For a 3D access environment or platform to be inclusive, access needs to be equitable, addressing a person's requirements until their experience aligns with the standard that is set for all. Adopting universal design principles and building multimodal systems can help increase a project's usability and inclusiveness. Designing to reach the greatest audience possible avoids the need for adaptations, which can cause users to feel excluded or singled out.[35]

## *Employ Robust Annotations*

Annotations, whether existing in the viewing environment or as supplementary material, need to be robust enough to meet the needs of the highest level user envisioned. The elements below may be considered as a starting point for this discussion:

> An annotation system designed to address the needs of academics working with 3D content must address five layers of information relative to the modeled environment: the **source material** used by the content creator to inform the reconstruction, **introductory information** to explicate the environment for users, **paradata** documenting the processes used during its creation [and interpretive decisions], **academic argumentation**, and **paratextual** information created by peer reviewers, editors, or secondary users.[36]

When dealing exclusively with in-environment annotations, Papadopoulos and Schreibman write that in-environment annotations are meant to explain and contextualize and offer scholarly scaffolding:

> For example, the 3D (re)constructions may offer one version of a building; however, evidence that supports alternative versions of certain architectural features may be represented by other models accessible in-world through a pop-up box or by replacing the current version of a feature with other possible versions; areas of uncertainty may be rendered in different colours and shading to indicate hypotheses, sources, and surviving evidence; or, ambiguous features may be toggled on and off or replaced by alternative versions, also indicating how other elements will be affected by these changes (e.g. a larger door opening may indicate a lighter roof structure).[37]

Moving forward, the 3D community will need to consider ways that scholarly annotation can be standardized to increase interoperability across platforms and allow for greater publication opportunities. Concerns regarding issues of version control and editing pipelines for annotated 3D materials need to be addressed. If agreement about managing annotation workflows can be met, publishers will be furthered empowered to take on 3D projects.

## *Set Standards for Peer Review*

Peer review for 3D scholarship could be modeled on past projects that were created explicitly to review digital scholarship such as NINES (Networked Infrastructure for Nineteenth-Century Electronic Scholarship), and its sister sites 18thConnect, MESA, ReKN, and ModNets.[38] However, these projects, which were once robustly active, have lapsed into silence—from either lack of funding, lack of staffing, or both. They still serve as a snapshot of best practices for a window in time in the realm of electronic scholarship, but without new accessions, any cutting-edge work being done is not represented.

The danger of orphaned, well-intentioned, and even successful projects looms large in the digital realm, and, for the sake of promotion and tenure, a new construct for peer review in the 3D realm should look seriously at sustainability. In lieu of a formal evaluating body, the 3D community could follow Geoffrey Rockwell's "Short Guide to Evaluation of Digital Work"; the more recently penned *Guidelines for the Professional Evaluation of Digital Scholarship by Historians* put out by the American Historical Association; the "Guidelines for Evaluating Digital Scholarship" in the Society for American Archaeology's *Report of the SAA Task Force on Guidelines for Promotion and Tenure for Archaeologists in Diverse Academic Roles*, which includes recommendations for evaluating 3D modeling and VR scholarship; and the College Art Association and the Society of Architectural Historians' *Guidelines for the Evaluation of Digital Scholarship in Art and Architectural History* .[39]

## Agree Upon Format for Citing 3D Data

It is crucial that scholars, information specialists, commercial and construction practitioners, and other users of 3D (or 4D, if one includes a time element) content begin to formalize and establish their respective documentation practices. While scholars have been painfully aware of the need for proper attestation practices since the 1990s, and that realization has given rise to initiatives such as the Cultural Virtual Reality Organisation (CVRO) and the London Charter, no initiative has led to the articulation of a concrete set of practices that we might find affiliated with the International Organization for Standardization (ISO) or articulated as a 3D equivalent to the *Chicago Manual of Style*.[40] A good deal of discussion has emerged from literatures ranging from virtual heritage to digital construction, historical GIS, the digital humanities, and other fields articulating documentation requirements, and based on those writings we recommend the development of 3D citation practices that meet the requirements of 3D scholarship (see table 6.4).

**TABLE 6.4**

Good/Better/Best recommendations for 3D data citation practices

| Tier | Recommendation | Examples |
|---|---|---|
| Good | Citations contain three components: publication data, bibliographic data, and paradata. | Publication data should communicate the name of the dataset, the identities of its creators, the name of its publishers or host institutions, the object's metadata (i.e., keywords), **its location and its publication and copyright status (e.g., proprietary versus open source)**. Bibliographic data should identify the name and provenance of all data sources that gave rise to the model. Paradata is a concept that has generated interest in multiple domains and with it multiple definitions, but for our purposes its definition can be reduced to the following: paradata communicate the decision-making and methodologies that gave rise to the model. See table 4.1 in chapter 4, "Metadata Requirements for 3D Data." |

| Tier | Recommendation | Examples |
|---|---|---|
| Better | Multimodal citations | Discussion and examples of 3D model documentation have typically centered on metadata and the use of software with text-entry fields to attach inscribed metadata to the given model. However, as mentioned earlier in the chapter, CHI has a Digital Lab Notebook that can provide a pathway from creation to publication. Scholars seeking to describe the workflow underlying a given model, for example, might also take a page from the construction industry and use schematic diagrams to describe the workflow and indicate important decision points associated with the data's construction (see figure 6.2). Other scholars, wishing to follow the interpretive reasoning behind a model, might wish to see prior versions of that model expressed in 3D. |
| Best | 3D models that are extensible and semantic | Further structuring data with Semantic Web technologies such as RDF (Resource Description Framework) and OWL (Web Ontology Language) support the rapid aggregation from multiple sources of data relating to a given domain or topic. |

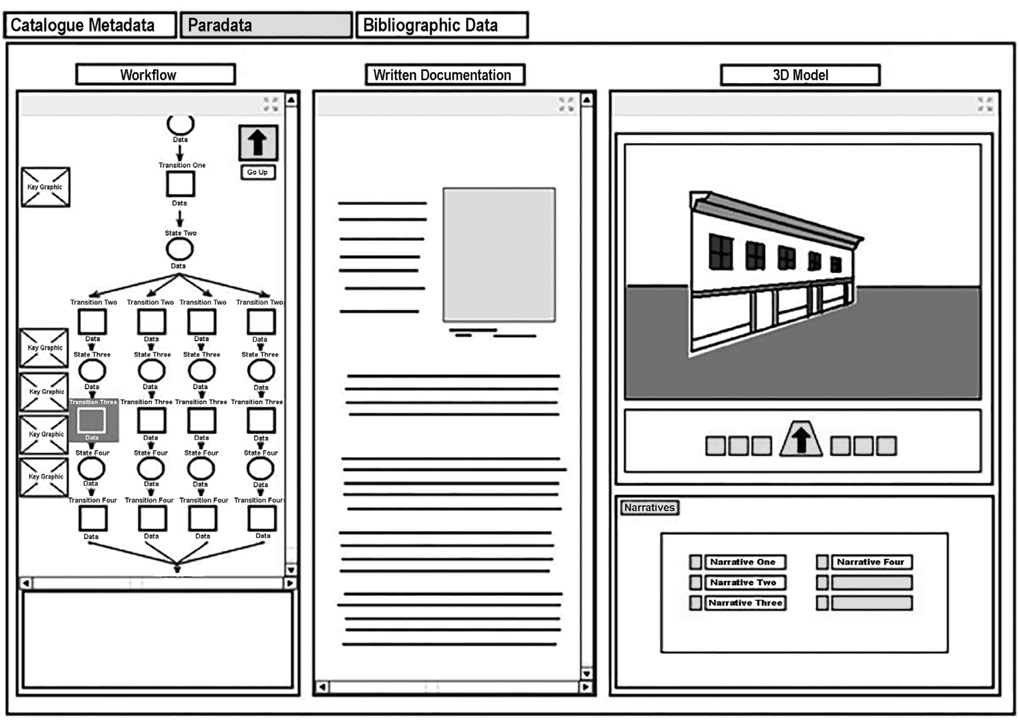


**Figure 6.2**
Mockup of multimodal expression of paradata

# Conclusion

Discovery and access are essential for the dissemination and use of 3D material. By defining the various modes of 3D data, this chapter has touched on a myriad of production methods and file outputs that frame conversations about how people store and share 3D materials. This discussion is critical for the construction of useful discovery tools and interoperability standards as the field seeks long-term sustainable workflows. Standards will need to not only address crosswalking metadata schemata generated in connection to methods of production, but also find a solution for viewing 3D material across platforms. The issues around viewing platforms also highlight the need to formalize how supplemental materials in the forms of annotation, embedded resources, tour features, and the like are integrated with the computer model and translated to other platforms as content is moved and preserved.

At the heart of this discussion are the audiences producing, using, and reusing 3D data. Reflecting on user needs can assist the 3D community in developing technical requirements and identifying implementation or use limitations. Future work for 3D practitioners needs to address gaps around accessibility, whether by those without access to high-speed internet connections or by the disabled. Additionally, in terms of scholarship and publication, if a community goal is for the model to become the site of academic argument, issues regarding citation and peer review will need further attention. Citation for 3D material must include far more than 3D coordinates (*x*, *y*, *z*, *h*, *p*, *r*), but address geometry, metadata (publication and bibliographic), and paradata. It is recommended that peer review of digital work have a solid framework for evaluation that is posited on access and annotation of the life cycle of 3D materials. Discovery and access become possible with the careful integration of the lessons and best practices communicated in the other chapters of this book and with a focus and dedication to the audiences that make up the 3D ecosystem.

# APPENDIX 6A
## Information needed to support long-term access to different modes 3D Data

**TABLE 6.A.1**

Modality: Manual

| Information | Examples |
|---|---|
| Source Material | Creative expression, documents, or photographs |
| Method of capture | Geometry constructed with modeling software, which could be a polygonal surface modeler, solids modeler, in-world modeler, or similar. Software ranges in complexity from SketchUp to 3ds with data structures dependent on output (e.g., real-time vs. high-resolution animation). The models are possibly augmented with texture, materials, and/or lighting. |
| Hardware/software needed | There are over 100 modeling software packages that run on a variety of hardware platforms. The challenge is the amount of data in proprietary software that are dependent on specific versions of specific software applications. See Wikipedia, s.v. "List of 3D modeling software," last modified September 25, 2021, 1:10, https://en.wikipedia.org/wiki/List_of_3D_modeling_software. |
| Output files | Raw model file(s) whether connected or individually; digital research files related to the modeled environments; related textures maps, materials files, palettes, and shadow maps; physical archives related to the project (e.g., notes, physical photos, collected reference material); metadata; paradata; and text publications related to projects (see also maximum files for preservation below). |
| Derivatives | Could include interactive environment, animation, static images, models transferred to other file formats for 3D printing, secondary models created by others to explore alternative reconstructions, teaching and learning objects; documentaries or film productions that include content from the model; or VSim files formats (.vsim, .nar., .ere), in instances of reuse by original creator or secondary scholars, depending on the research objectives. |
| Methods of interaction | Depending on the use case, could be with a real-time viewer, uploaded into other 3D content types (e.g., virtual world, virtual immersive environment), or mixed with other 3D content types for use in other viewers. |

| Information | Examples |
|---|---|
| Minimum files for access | Presuming intent is reuse as 3D geometry and interaction as content creator intended: final version of the 3D model(s) in preservation file format and native file format; final textures maps, materials files, palettes, and shadow maps (file structure may be critical); stable version of the software required to view and interact with said files (e.g., Creator, 3ds, Maya, SketchUp/Google Earth); metadata and paradata that describe the projects and decisions made during the creation of the model. If a real-time environment, the final aggregated binary files and the software necessary to "fly" the model. If a Google Earth model, any GIS-related files and spreadsheets. |
| Maximum files for preservation | 3D computer model(s) in different formats (e.g., .obj, .dae, native file formats); versioned copies of the 3D model files; textures maps, materials files, palettes, and shadow maps that go with the different model versions (file structure may be critical); stable version of the software required to view and interact with said files (e.g., Creator, 3ds, Maya, SketchUp/Google Earth); videos generated from the computer model; static images generated from the computer model (screenshots and **renderings**); metadata and paradata that describe the projects and decisions made during the creation of the model; research files and documents in various formats (scans, PDFs, bibliographic information, etc.). If a real-time environment, various iterations of the aggregated binary files and the software necessary to "fly" the model. If a Google Earth model, GIS-related files and spreadsheets if time periods are included. If used for creation of other materials (e.g., teaching resources or a film production), work files related to the final output and copies of that final output; analog documents and artifacts relating to the 3D model; correspondence related to the project; and publicity/marketing related to the project. |

**TABLE 6.A.2**

Modality: Scanned volumetric

| Information | Examples |
|---|---|
| Source material | Real-world object, time series volumes (fMRI). |
| Method of capture | Computed tomography (CT), magnetic resonance imaging (MRI), functional MRI, positron emission tomography (PET). |
| Hardware/software needed | Scanner (make, model, setting). |
| Output files | Package of images in sequence. |

| Information | Examples |
|---|---|
| Derivatives | JPG stacks, rendered/interpolated surfaces or volumes that could include information about the characteristics of the object (isosurfaces), colormaps, or a color lookup table (which can also have opacity from alpha channel). |
| Method of interaction | Desktop or web applications (ImageJ, Box DICOM, or a plethora of other (especially medical) applications. |
| Minimum files for access | Ordered stack of images (generally TIFF or JPG) with resolution, spacing of slices, number of slices. |
| Maximum files for preservation | Original DICOM files, TIFF stacks (or JPG derivatives), interpolated volumes or surfaces, documentation of capture and workflow. |

**TABLE 6.A.3**

Modality: Scanned surface

| Information | Examples |
|---|---|
| Source material | Real-world object. |
| Method of capture | Contact, active, conoscopic, structured light, modulated light, laser, microscribe. |
| Hardware/software needed | Scanner, software, lighting rig, enclosure, turntable. |
| Output files | OBJ, PLY, STL, X3D. |
| Derivatives | Lower poly count models for better web accessibility, portion of model for preservation of detail via web deliverable. |
| Method of interaction | Desktop application such as MeshLab, online viewer such as Sketchfab. |
| Minimum files for access | Constituent files of 3D model and metadata. |
| Maximum files for preservation | Original scan files, cleaned scan files, decimated files, documentation of capture and workflow. |

**TABLE 6.A.4**

Modality: Photography-based

| Information | Examples |
|---|---|
| Source material | Real-world objects captured through a variety of image formats from historical photos to terrain photos to photos of objects. |
| Method of capture | Flyover (landscape), light tent with turntable, circling object. |
| Hardware/software needed | GoPro, DLSR camera. See Wikipedia, s.v. "Comparison of photogrammetry software," last modified October 24, 2021, 20:55, https://en.wikipedia.org/wiki/Comparison_of_photogrammetry_software. |

| Information | Examples |
|---|---|
| Output files | OBJ, PLY, STL, X3D (raw and cleaned-up model; metadata, paradata on production). |
| Derivatives | Lower poly count for web display, watertight for printing. |
| Method of interaction | Sketchfab, VR environments, stand-alone players like 3DHOP. |
| Minimum files for access | Constituent files of 3D model, metadata. |
| Maximum files for preservation | RAW, unaltered photos; derived JPGs for stitching; unaltered, stitched 3D model; cleaned model; metadata of workflow. |

**TABLE 6.A.5**

Modality: Procedural/algorithmic

| Information | Examples |
|---|---|
| Source material | "Direct" import: GIS, laser scans (3D point clouds imported as polygons), photogrammetric data (imported as polygons/mesh such as .obj, .dae), photos (as textures). "Indirect" import: used in process to create data imports and GIS attributes—architectural plans, excavation maps, architectural drawings, photos, ethnographic/ethnohistoric descriptions. |
| Method of capture | Geometry generated from GIS data and rule-based script (computer graphics architecture—CGA) as well as expertise/interaction with data in software; qualitative and quantitative. |
| Hardware/software needed | Esri CityEngine (proprietary) and Terragen (work with GIS data); Acropora, Bryce, Modo, Cinema 4D, Esri CityEngine, Grome, Houdini, HyperFun, OpenSCAD, Softimage, VUE, PlantFactory, Xfrog, SpeedTree, Grasshopper 3D |
| Output files | Esri CityEngine (proprietary) and Terragen (work with GIS data); Acropora, Bryce, Modo, Cinema 4D, Esri CityEngine, Grome, Houdini, HyperFun, OpenSCAD, Softimage, VUE, PlantFactory, Xfrog, SpeedTree, Grasshopper 3D3D terrain models, and subsets of 3D models with terrain; .dae, .dxf, .fbx, .gdb, .kml, .kmz, .obj, .osm (import only), .vob (export only), .abc (export only), .rib (export only); Unreal Engine (export only), .3ws (CityEngine webscene), .3VR (standard VR format—export only); unlike exporting these data from a GIS, you can specify whether you want to retain materials and textures, whether you need to write the normals or even triangulate the meshes; .cga file (text file with script/code) serves as paradata and possibly as metadata depending on comments. |
| Derivatives | 3D single object models (as polygons), 3D terrain models, 3D terrain models with 3D architectural models/textures to be used in various software. |
| Method of interaction | Within CityEngine or CityGML. Export to ArcGIS Pro, WebGL environments, game engines (e.g., Unity, Unreal Engine), 3D object viewers (e.g., 3DHOP, Sketchfab). |

| Information | Examples |
|---|---|
| Minimum files for access | CGA file (text), GIS data (specifically speaking of CityEngine). |
| Maximum files for preservation | Presuming intent is reuse as 3D geometry and interaction as content creator intended: final version of the 3D model(s) in preservation file format and native file format; final textures maps, materials files (file structure may be critical); stable version of the software required to view and interact with said files (e.g., CityEngine, but other 3D software programs for exports); metadata and paradata that describe the projects and decisions made during the creation of the model. If a real-time environment, the final aggregated binary files and the software necessary to "fly" the model. If a Google Earth model, any GIS-related files and spreadsheets. |

**TABLE 6.A.6**

Modality: Digital terrain

| Information | Examples |
|---|---|
| Source material | Satellite imagery, GIS data (vector [contours] or raster [DEM]), aerial imagery (photogrammetry/stereo pairs), airborne lidar, height maps. |
| Method of capture | Vector to raster conversion (topo to raster)—interpolation; 3D points to raster (e.g., total station, lidar)—interpolation; stereo pairs (aerial imagery); photogrammetric methods (satellite/aerial imagery); TINs. |
| Hardware/software needed | GIS software, e.g., GIS, ArcGIS; photogrammetric (SFM) software, e.g., Agisoft PhotoScan (now Metashape); lidar processing software, e.g., Global Mapper, CloudCompare). Hardware: high processing power and RAM. |
| Output files | Raster files such as Esri GRID, GeoTIFF, DEM, ASCII, STRM1, STRM3, STRM30, ASTER, GTOPO30. |
| Derivatives | Lower resolution raster files; heightmaps; urban DEM; digital surface model (DSM); digital terrain model (DTM); digital elevation model (DEM). |
| Modes of interaction | Desktop, mobile, web applications. |
| Minimum files for access | Raster file (e.g., Esri GRID, GeoTIFF) |
| Maximum files for preservation | Original data sources (e.g., total station points, 3D points, contour lines), interpolated raster surface (e.g., Esri GRID, GeoTIFF); surface derivatives (e.g., heightmaps, DSM, etc.). |

**TABLE 6.A.7**
Modality: Virtual world

| Information | Examples |
|---|---|
| Source material | The most useful definition of a virtual world contends that it is a computer-simulated representation of a world with specific spatial and physical characteristics, and users of virtual worlds interact with each other via representations of themselves called "**avatars**." Virtual worlds are three-dimensional environments in which you can interact with others and create objects as part of that interaction. Confusion over the term has resulted in a fragmented understanding in the existing literature of what a virtual world is and is not. There are a range of virtual worlds to choose from, which include fantasy, sport, historical, and science fiction. Some are loosely based upon the real world, but others, such as fantasy worlds, are completely disconnected from the real world, which is also part of their attraction. To further complicate this problem, a variety of terms are used in the literature to label the technology: virtual world (VW); virtual environment (VE); multiuser virtual environment (MUVE); massively multiplayer online game (MMOG); immersive virtual world (IVW); serious virtual world; social virtual world; and synthetic virtual world. Most recently, a virtual world has been defined as "Shared, simulated spaces which are inhabited and shaped by their inhabitants who are represented as avatars. These avatars mediate our experience of this space as we move, interact with objects and interact with others, with whom we construct a shared understanding of the world at that time" (Carina Girvan, "What Is a Virtual World? Definition and Classification," *Educational Technology Research and Development* 66, no. 5 [2018]: 1099). |
| Method of capture | Geometry constructed with modeling software, which could be a polygonal surface modeler, solids modeler, in-world modeler, or similar. Software ranges in complexity from SketchUp to 3ds with data structures dependent on output (e.g., real-time vs. high-resolution animation). The models are possibly augmented with texture, materials, and/or lighting. |
| Hardware/software needed | There are over 100 modeling software packages that run on a variety of hardware platforms. The challenge is the amount of data in proprietary software that are dependent on specific versions of specific software. See Wikipedia, s.v. "List of 3D modeling software," last modified September 25, 2021, 1:10, https://en.wikipedia.org/wiki/List_of_3D_modeling_software. |
| Output files | Raw model file(s) whether connected or individually; digital research files related to the modeled environments; related textures maps, materials files, palettes, and shadow maps; physical archives related to the project (e.g., notes, physical photos, collected reference material); metadata; paradata; and text publications related to projects. See also maximum files for preservation below. |

| Information | Examples |
|---|---|
| Derivatives | Could include interactive environment, animation, static images, models transferred to other file formats for 3D printing, secondary models created by others to explore alternative reconstructions, teaching and learning objects; documentaries or film productions that include content from the model; or VSim files formats (.vsim, .nar., .ere), in instances of reuse by original creator or secondary scholars, depending on the research objectives. |
| Method of interaction | Depending on the use case, could be with a real-time viewer, uploaded into other 3D content types (e.g., virtual world, virtual immersive environment), or mixed with other 3D content types for use in other viewers. |
| Minimum files for access | Presuming intent is reuse as 3D geometry and interaction as content creator intended: final version of the 3D model(s) in preservation file format and native file format; final textures maps, materials files, palettes, and shadow maps (file structure may be critical); stable version of the software required to view and interact with said files (e.g., Creator, 3ds, Maya, SketchUp/Google Earth); metadata and paradata that describe the projects and decisions made during the creation of the model. If a real-time environment, the final aggregated binary files and the software necessary to "fly" the model. If a Google Earth model, any GIS-related files and spreadsheets. |
| Maximum files for preservation | 3D computer model(s) in different formats (e.g., .obj, .dae, native file formats); versioned copies of the 3D model files; textures maps, materials files, palettes, and shadow maps that go with the different model versions (file structure may be critical); stable version of the software required to view and interact with said files (e.g., Creator, 3ds, Maya, SketchUp, Google Earth); videos generated from the computer model; static images generated from the computer model (screenshots and renderings); metadata and paradata that describe the projects and decisions made during the creation of the model; research files and documents in various formats (scans, PDFs, bibliographic information, etc.). If a real-time environment, various iterations of the aggregated binary files and the software necessary to "fly" the model. If a Google Earth model, GIS-related files and spreadsheets if time periods are included. If used for creation of other materials (e.g., teaching resources or a film production), work files related to the final output and copies of that final output; analog documents and artifacts relating to the 3D model; correspondence related to the project; and publicity/marketing related to the project. |

**TABLE 6.A.8**

Modality: Immersive virtual environment

| Information | Examples |
|---|---|
| Source material | Virtual "environments" are distinguished from virtual "worlds" to emphasize the use of a headset for the experience and that they do not necessarily require a sense of physical place. A virtual environment is more focused on creating an immersive experience, as dictated by the creator. In addition, to distinguish it from Mark Bell's definition of "virtual worlds," immersive virtual environments do not usually have (as yet) a time element in the way that things like Second Life do, where the world continues on without the user's engagement. |
| Method of capture | Construction of immersive virtual environments can happen two ways: outside the environment or inside the environment. Production outside the environment can range from geometry constructed with modeling software to experimental. In-environment creation includes tools such as Tilt Brush or Sketchbox, and will likely grow as immersive technology develops. |
| Hardware/software needed | Typically a headset display will interface with a software application through the device or through an application on a mobile phone to allow for experiences to run. Sometimes hand controller, sensor stands, and/or headphones may be necessary to navigate the software within the headset. While the combination of technologies can vary, there are tailored specifications for display refresh rates, graphics cards, screen resolution that are needed for certain digital immersive software to run. Often released by hardware producers, software development kits (SDKs) are used in the development of many extended reality products. Some hardware producers offer emulators for software developers to use if they do not have headsets to test with. In order to be disseminated more widely, these digitally immersive extended reality products usually need to be packaged for one of the app stores where they can be released and played. |
| Output files | Application/package release to an app store such as the Apple App Store, Google Play Store, YouTube 360, Facebook 360, Little Star, Jaunt, 360 RIZE/360Heros, Discovery VR, WAVRP, 360s.tv (adult content), Oculus App Store, Steam VR. |
| Derivatives | Reuse by original creator or secondary scholars: Could include interactive environment, animation, static images, models transferred to other file formats for 3D printing, secondary models created by others to explore alternative reconstructions, teaching and learning objects; transfer to virtual worlds |
| Method of interaction | Headset, controllers. |
| Minimum files for access | Adherence to specific app store or platform distribution requirements. |

| Information | Examples |
| --- | --- |
| Maximum files for preservation | 3D computer model(s) in different formats (e.g., .obj, .dae, native file formats); versioned copies of the 3D model files; textures maps, materials files, palettes, and shadow maps that go with the different model versions (file structure may be critical); stable version of the software required to view and interact with said files (e.g., Creator, 3ds, Maya, SketchUp, Google Earth); videos generated from the computer model; static images generated from the computer model (screenshots and renderings); metadata and paradata that describe the projects and decisions made during the creation of the model; research files and documents in various formats (scans, PDFs, bibliographic information, etc.). If a real-time environment, various iterations of the aggregated binary files and the software necessary to "fly" the model. If a Google Earth model, GIS-related files and spreadsheets if time periods are included. If used for creation of other materials (e.g., teaching resources or a film production), work files related to the final output and copies of that final output; analog documents and artifacts relating to the 3D model; correspondence related to the project; and publicity/marketing related to the project; emulator program if hardware no longer exists. |

**TABLE 6.A.9**

Modality: Games

| Information | Examples |
| --- | --- |
| Source material | Games will have unique preservation challenges, based on what kind access the preserved material should provide, e.g., a walk-through that reduces the game to a singular experience or a virtual machine that allows interactive play. Games can have components from the real or imagined world, and components can also be algorithmically generated. |
| Method of capture | Constructed base structures, manipulatives, scenes that define "relationships between objects, including location and size" (Wikipedia, s.v. "3D computer graphics, last modified November 21, 2021, 4:47, https://en.wikipedia.org/wiki/3D_computer_graphics). |
| Hardware/software needed | See the following lists on Wikipedia:<br>• "List of 3D computer graphics software," https://en.wikipedia.org/wiki/List_of_3D_computer_graphics_software<br>• "List of 3D modeling software," https://en.wikipedia.org/wiki/List_of_3D_modeling_software<br>• "List of 3D rendering software," https://en.wikipedia.org/wiki/List_of_3D_rendering_software. |
| Output files | Package released to platform of choice. |

| Information | Examples |
|---|---|
| Derivatives | Audiences watching games, video walk-throughs, virtual machine preservation. |
| Method of interaction | First- or third-person POV (third-person perspective is often used as a camera position in the game) with additional actions dependent on the controller and platform in use. |
| Minimum files for access | Minimum package required for publication to platform of choice. |
| Maximum files for preservation | Versions of the game in development, walk-through, metadata of construction and intended use, virtual machine of game. |

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