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MUSEUMS AND DIGITAL ARCHIVES: A QUALITATIVE STUDY OF VERTEBRATE COLLECTIONS

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SAGE E. CROMWELL
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MUSEUMS AND DIGITAL ARCHIVES:
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BY THE COMMITTEE CONSISTING OF

Dr. Jaqueline Lungmus, Chair

Dr. Lena Cole

Dr. Steven Gullberg

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Name: Sage E. Cromwell

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Abstract: The museums we know of today had their start from both an interest in collecting cultural items for entertainment, as well as to use as educational tools. Since then, it has morphed into a varied stewardship of researching prehistoric specimens, protecting humanity's commonwealth, and preserving such items for future generations. In the modern age, this includes digital aspects of museology that have become increasingly necessary among institutions to properly maintain their public trust and relevancy through collaborative research, educating their audiences, and interactions with benefactors. Digitizing paleontological collections is a growing element within an institution's stewardship of responsibility towards both their local patrons and the global community. However, there are challenges that must be addressed and resolved while integrating this aspect of preservation into a museum's archival practices. Digitization is a relatively new integration, and thus there is no shared baseline of ethics, laws, or best practices surrounding actions or procedures that are shared across other areas in the field of museology. This qualitative study explores the current best practices of museums regarding digitization- how they utilize technology, tools and resources to enhance their digital archives, as well as evaluate the long-term strategies they currently implement. The impact of this thesis is to add evidence of how the digitization of specimens has been integrated into the field for the past few decades and to highlight its growing vitalization in the modern world of global interconnection. The survey responses are aligned through themes to better highlight what common advantages and disadvantages that museums must navigate when incorporating digitization into their daily responsibilities.

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Chapter 1: Introduction

Pros of Digitization		
Increased Global Interconnection	Increased Collaborative Research and Networking	Fossil Replicas Made In A More Safe Method
Increased Public Trust	Fulfillment of Ethical Duties	Incorporate Paleontology Data with Other Sciences
Increased Open Access	Fulfillment of both Mission and Vision Statements	Increased Access to Contextual Data
Increased Relevancy through Interactions with Patrons	Access to Fossils without Handling, thus Preserving and Protecting the Fossils	Easier and Safer Loan Protocols
Cons of Digitization		
Start-up Costs	Lack of Digital Storage Space	No Long-term Sustainability
Training of Staff	Lack of Standard Best Practices or Protocols	Staff Error in Digitization
Staff Rotation	Lack of Resources	Trial and Error in Methodologies
Requires Long Timelines	Complex Process, both to Use and Impliment	Loss of Data with Collection Transfers

Figure 1. Pros and Cons of Digitization.

1.1 Current Situation and Evaluation

Museology has been established as a theoretical, methodological, contextual, and ever-changing complex field of study. Museums have four major responsibilities- to collect, preserve, interpret, and display objects of significance for the education of the public and scientific research (Fan and Wang 2020; Macdonald 2006). To maintain long-term stability, museums also must have a core goal to stabilize and increase their relevance through engagement with their

audiences and network through research collaboration with others in their field (see Figure 1). They focus on using education and enjoyment to connect with their visitors' sense of humanity and expand upon their patrons' experience in the world (Brown 2020). Natural history museums especially have this goal, as biological specimens are primary scientific data and therefore, a public and scientific asset. They can now provide a greater amount of data in sciences such as ecology, conservation, and integrated sciences in a wider range than ever before.

However, due to the fragile nature of vertebrate paleontology specimens, preservation is exceptionally a core aspect to this field. In the modern age and with a mass increase in both globalization and accessibility for research, digitally preserving these irreplaceable fossils have become an integral aspect to preservation as well. Digital planning, management, standardization, and open-access sharing have become necessary to best connect and expand upon a natural history museum audiences' knowledge of the natural world (Colella et al. 2020; Bakker et al. 2020; Crew 2017). In addition to these changes, natural history museums must adhere to legal, ethical and political guidelines that affect how they are able to operate daily and the decisions they must make (Lindqvist 2012).

In recent decades, museums have increased their efforts to expand their participation in digitizing their paleontological collections. These efforts have included not just creating databases of contextual information or 2D photographs connecting the data to the specimen but also gathering digital scans of the specimens using various methods of 3D technology. Such examples would be surface or light scanning, CT scanning, and photogrammetry (using multiple angled photographs that combine to create a 3D image). The inclusion of preserving their archives in a 3D digital format is due to several factors, including an increased availability in

technology and open access of data, as well as to reflect the growing number of interconnected research interests across both national and international projects.

However, the digitization of specimens can often be more challenging than anticipated. Museums must first have the specimens cataloged and available for digitizing before beginning the transferring process. Next, the institutions must have the digitization equipment required, as well as the available and knowledgeable staff to transfer the data. Additionally, while technological advances are increasing, other vital supportive aspects are lacking, such as the allocation of museum resources, legal and ethical protocols, and the long-term ability to maintain the data (see Figure 1). These challenges are amplified by how the available technology is integrated into individual museums, thus each museum can have varying solutions for digitizing their vertebrate paleontology collections, creating a lack of cohesive and accessible protocols and standardization of action for troubleshooting any issues (Woodward 2012).

The current state of preservation through digitization is still in the early stages, and institutions have begun to incorporate certain aspects of digitizing into their collection practices through building a digital network internally with the resources they have, utilizing different departments in their museum, as well as externally through networking connections and resources. At the core of these incorporations is how a museum organizes the development and integration of workflows into an established collections archive (Karim et al. 2016). While this is often the most beneficial movement, this form of community-vetted, field-wide established protocol has yet to be implemented as a standard. This is partially due to an over abundance of backlogged specimens that must then be addressed, with staff then feeling overwhelmed at the required tasks in addition to their other responsibilities.

Museums- and specifically collection staff - must make informed decisions while deciding when, how and with what resources that the collection will be transferred to which type of digital media. This concept of learning how to navigate digitization through a group effort will enhance and enrich the goal of attaining best practices through preserving specimens in an established and concentrated format. These efforts are connected with the result of audiences, various cultures, and increased power in the professional research networks as a whole (Macdonald 2006). As such, this often requires the relevant parties to share their insight, available tools, and expertise in a group setting in order to reach the most efficient problem solving and resource management allocation (MacFadden et al. 2016). These aspects are critical for increasing the efficiency levels in their archive systems, which will then increase their research relevancy and public relations network (Bakker et al. 2020).

My thesis qualitatively studies the current best practices of museums that are digitizing specimens in their vertebrate paleontology collections to assess similarities and differences that can be used to increase field-wide protocols and guidance of daily practices. Such collections have an increased use of technology and digitization in the past few decades due to a number of factors. These include the fragility of their specimens, the enhanced research and knowledge of their collections, as well as the global relevance for the specimen's data. Thus, vertebrate paleontology collections in natural history museums are an ideal subject for the study.

Some of the goals of this study are to understand how many specimens have been digitized, what tools institutions are using to digitize them, and what benefits and challenges the institutions have in the process. These are asked to gain an understanding of where the current situation is in individual museums. The next goal is to assess how vertebrate paleontology collections determine their best practices for standardizing the process of digitizing and storing

their data for public access, over both a short and long period of time? Other questions such as what challenges they are facing, how security and storage issues are handled, and what solutions they are incorporating, if any, to their practices. This will help answer what type of considerations individual museums are concerned with and if that can be applied on a field-wide level in order to increase the overall success in the collection's research, preservation, and collaboration efforts.

1.1.1 Overview of Digitization in Vertebrate Paleontology Collections

A collections department is a core responsibility of a museum- to be entrusted with irreplaceable items for the preservation, display, and education of its audience to fulfill their mission and vision statements in an ethical, legal, and moral manner. To properly log and organize each individual specimen, every item must contain locality, taxon, and assigned archival numbers (Silva Mano et al. 2024). Additionally, maps of various localities of the dig sites, copies of permits, and catalogs are required for the collection as a whole. This layered documentation requirement allows the museum to have organized control regarding the information within the collection, and then catalog the information with detailed individualization of the items. Without this aspect, a lot of the context within a fossil is gone. An important element of collections is to gather, maintain and evaluate the context of a fossil to the best of the museum's abilities (Whitaker and Kimmig 2020). Maintaining context has drastically increased with the incorporation of technological aid- online datasets, accessibility with reduced handling of fragile specimens, as well as a more in-depth and increased research ability regarding specimen data. These aspects have benefited the field of paleontology and have become an integral daily practice across the field.

1.1.2 Evaluation of Major Information Gaps

Managing digital media is not an easily added responsibility to the museum's collection department- it is a multi-faceted, complicated, and powerful tool that an institution can use to remain relevant in the modern globalization of the digital age (Geismar and Müller 2022). While there is a growing need to consider accessible outreach, there are still important aspects to accommodate for based on the available resources to every collection. There are studies that have been conducted in order to understand elements of these incorporations that will be discussed in this thesis, however, there is much more research and implications into the process of realistically incorporating digitization that must be understood to better create a stable and sustainable field-wide code of conduct for museums to follow. These aspects will also be discussed in later chapters.

Additionally, there are many different media types that can be used to archive specimens into a digital manner that are also difficult to study the successful incorporation of on a large scale. Videos, photographs, audio descriptions, and 3D scans can all be utilized material that the museum can benefit from introducing into its practices. These categories can be vital for creating different data sets in the most advantageous systems for the museum. Having various forms of data can also allow for any necessary changes or back-up usage while in the maintenance phase of the data once they have been transferred from physical specimens, depending on the information gleaned from the archives (Valev 2016; Hirshon 2018). However, every form of digital media has different requirements for the staff to learn, which can then make it difficult to study the impact across a long time period to measure success of the various formats of digitization.

1.1.3 Importance of the Topic

Institutions have a stewardship, ethical, and legal obligation to preserve specimens that are then to be used for research, educational, and entertaining purposes. Through these duties, museums create practices, protocols, and codes through which to adhere to when issues or changes in the needs of the community arise. Creating standards of digital collections across the field of museum management negates the need for unnecessary "reinventing of the wheel"-type of behavior amongst museums, and allows for growth and adaptation to progress more steadily (Ronchi 2009). By outlining standards across the field of museology, digital preservation can be enhanced and expanded more quickly than individual museums attempting to branch into the new element of digital preservation on their own.

Digital preservation enhances both the life of the specimen on a digital platform, as well as the accessibility for the specimen to be more widely studied. This concept establishes that multiple groups of people are needed to formulate a field-wide best practice. It is estimated that there are over three billion biologically diverse specimens that have been curated and researched (Ellwood et al. 2015). The data that has been built from these mass collections has been irreplaceable in understanding the changing anthropogenic effect of biodiversity loss in the modern age, as well as ecological elements of climate change over eons of time. Additionally, digitization also requires enhancing the collaboration and shared learning of paleontologists across borders to understand how to obtain, manage and interpret specimen data (see Figure 1). The information can also be shared at both a faster and easier rate to multiple research interests, such as evolutionary, ecological, or chemical measurement research projects (Colella et al. 2020).

Institutions that work with paleontological specimens have recently experienced an increased relevance in other scientific areas, such as conservation and global climate sciences.

Researchers, more now than ever before, are critically requiring prehistoric data and have begun to request access to natural history collections and their documentations (Lendemer et al. 2020; Nelson and Ellis 2018; Bradley et al. 2014). Knowledge that cannot be understood in full without the depth of paleontological sciences and studies are now being integrated with other sciences in an increasingly irrevocable academic support system. However, this increase in vital interdisciplinary collaboration is not necessarily reflected in the natural history museum field's support through allocated resources (Bradley et al. 2014).

1.2 Historical Context of Object-based Collections

Since the earliest record of civilization in 530 BCE Mesopotamia, there have been museums that have collected items to put on display for the enjoyment and edification of the public. As the popularity of collecting items began to grow, museums expanded in number- as well as in responsibilities (Zaidi 2016; Simmons 2015). Natural history museums have, throughout time, been in the haze of where they belong in terms of categorical interaction with their purpose- to balance between relevancy with their audiences and the preservation and research of the past. In the modern age, museums are still lacking in a definitive place between education and entertainment, preservation of artifacts and maintaining a sustainable relevancy for the future. The International Council of Museums (ICOM) statutes vaguely define museums as a non-profit and permanent institution that provides services to society that promote its development through public interaction. They also allow access to their stewardship for research, education, and entertainment (Brown and Maireese 2018). Museums make their unique contribution to the public by collecting, preserving and interpreting the things of this world.

Paleontological collections within museums within the United States officially were distinguished into law in 1846, with the Smithsonian Institution, which has evolved into one of

the largest natural history collections worldwide (Gilmore 1941). These paleontological collections are no less subject to the technicalities and unclear boundaries as the remainder of the museums that steward them. Further, they can also be a discussion of controversy. Paleontology refers to the ancient world beyond humanity, containing fossils of plants, animals, and the timeline of the earth itself (Lendemer et al. 2020). Many of these fossils are the subject of discourse in terms of labeling taxa, which can also be changed over time as new information and context emerges across the field. These are examples of how the vertebrate paleontology collection within a museum does not abstain from being the subject of controversy and constant revisiting.

An artifact by itself is an important piece of prehistory, but it has very little meaning without its context. Vertebrate paleontology specimens especially, without context, cannot have credible meaning in addition to the interpretation of the field (Tang 2005; Page et al. 2015). While data gathered from the individual fossil itself can be helpful to a specific taxon, the context of where it was found creates an invaluable amount of data in the meaning and interpretation of the specimen, site, and overall area. This is why documentation and protocols are in place to protect and preserve the context through which the specimen is attached (see Figure 1). Protocols protect the data and its irreplaceable implications on broader global issues of ecological, conservation and climate change. Proper documentation is vital to upkeep the discipline-focused historical record of Earth throughout the ages (Vollmar Macklin and Ford 2010).

1.2.1 Evolution of Museums and Collections

Collection management is one of the foundations of museum responsibilities, as the information that is gathered from fossil individuals to entire past ecosystems contain the history

of life on Earth that is irreplaceable and unobtainable by any other method (Silva Mano et al. 2024). This branch of a museum's core duty formed from a tradition of restoration to a layered and an in-depth profession that utilizes the scientific method to preserve specimens for humanity's scientific investigation and multi-cultural benefit. (Smith 2010; Lendemer et al. 2020). Fossils that are accessioned are the museum's responsibility, and require multiple layers of documentation to preserve context, ethical and lawful requirements. The museum staff is tasked with cataloging, preserving, and organizing the specimens both in physical and digital form that are entrusted in the museum's collection department. Shared digitization began around 1999 to enhance access to a broader range of research in the paleontology field. By 2018, that effort was expanded to more than one billion biodiverse records worldwide (Nelson and Ellis 2018; Simmons 2015; Lendemer et al. 2020; Vollmar Macklin and Ford 2010). That has only continued to grow, with more museums experiencing the collaborative benefits (see Figure 1) of digitizing their collections for the purposes of research.

1.2.2 Modern Collection Standards and Methods

The overall quality of specimens in a vertebrate paleontology collection reflect what data is able to be extracted and used. Field data such as labels, Geographic Information Systems (GIS), and daily field notes can be connected to digital specimens and catalogs on third-party programs, which can assist with digital format translations by creating as much information from the primary source as possible. Specimen tagging mistakes are common due to a lack of standard digitized practices, and issues increase when the collections staff is not familiar with the details of the fieldwork that they are digitizing (see Figure 1). Reducing the amount of individual practices and increasing the use of standardized digital tools would create an environment of efficient and accurate correction of electronic records, while also reducing the need for re-doing

the same work by hand, which is a current practice in many museums (Vollmar Macklin and Ford 2010; Nelson and Ellis 2018). However, that possibly leads into devices not synching up, hot equipment, loss of signal, or crashing - leading to a loss in unsaved data. (Silva Mano et al. 2024; Reed et al. 2015). Hard copies of data are also still needed until a standardized and reliable method of digitization can be reached that is field-wide to ensure there is a multi-layer safety-net of contextual information (Smith 2010; Johnson and Carter 2019).

Fossils are collected in many different forms that are then brought in from the field into a museum or laboratory research environment. The staff must then add the fossils to the overall collection (Johnson et al. 2005). Often, the time commitment of transporting a fossil from the field to the lab or museum is extensive, and that process often causes specimens to arrive in a broken or otherwise fragile state. Unfortunately, field bias in the field of paleontology must be addressed as well. Collection, funding, and research can be heavily favored during the preliminary grant proposal and field collection stage. Museums must be sensitive to whether or not there is collection bias in their grant proposals, fieldwork, and preservation practices (Whitaker and Kimmig 2020). This bias can then be extended into what fossils are digitized and in what order. Researchers and institutions must make decisions based on considerations such as grant support or physical space in their laboratory.

Museums have an obligation to preserve their specimens for research, their current audiences, and future generations. An added benefit is that digital data such as images, can lessen or delete the need for travel to museums or the loaning process for specimens (Page et al. 2015). This can create a financial alternative where museums can allocate travel or borrow funds to meet the other needs in the museum. The efforts and resources of museums can create a

discourse between research projects, and digitalization can be a resource to bridge between conflicts of research, resources, finances and staff needs (Tang 2005; Card et al. 2021).

1.3 Vertebrate Paleontology Collection Responsibilities and Challenges

1.3.1 Functions

Another core function of museums is the process of loaning out specimens to other researchers or museums for exhibits. The key components of asking for specimen loans are the purpose for the loan, the description of materials needed in the loan, where the specimens will be kept during the duration of the loan, as well as who is responsible for the specimens. These aspects must be included along with all legal documents and permits required by the state and federal regulations of the government, as well as follow the ethical protocols of the lending museum. Often, museums require paperwork and a timetable as to when the specimens will be returned to the lending museum, as well as insurance quotes for certain specimens from the lender in case of loss or damage to the specimens. The museum must take precautions against losing or damaging the items in the mail, especially delicate and rare specimens. (Yale Peabody Museum 2024).

Loans are the current overall method of handling the process of sharing specimens, however, there is always a threat of damage, or risk of loss, or a delay in returned loans that must be considered, and can come with additional costs to the institution and researchers (Page et al. 2015). Intertwining digital databases into the best practices within a collection would assist institutions with lessening the risks that accompany loans, be able to expand on their collaboration ability, and enhance their reputation within the field of paleontology (see Figure 1). Systematic and organized collection management practices, both physical and digital, enhance an archives collection to cultivate an environment of smooth protocols and efficient sharable

research (Whitaker and Kimmig 2020). However, when loans are requested and granted in a digital format, some institutions do not yet have lending protocols in place. This process is often expensive, time-consuming and financially taxing on the museum to create legal documents for the lending party to sign.

Until the past few decades, this process was also aided by creating replicas for fossils. These were produced by physically molding and casting the specimens. The technological age has allowed for a shift in methods, allowing for 3D scanning and printing of digital models that have become more efficient, allowing for cheaper and more accurate fossil replicas to be made with one file (see Figure 1). This benefits both researchers, as physically making, storing, and causing further erosive damage to the specimens via molds or casts is significantly reduced (Matsui and Kimura 2022; Whitaker and Kimmig 2020).

Along with the damage that can occur when casting and molding, some specimen samples must have a small portion destroyed in order to be analyzed for research. During the loaning process, some institutions require a very detailed explanation on what they would need to do with the specimen to obtain the data through destructive testing, while others require a mold and cast to be made of the specimen before any testing is done (Card et al. 2021; Page et al. 2015; Johnson et al. 2005). When adding a digital copy of the specimen, the preservation of objects is not only intact in a digital space, it is able to be printed in a real-world replica of the model, without the inconsistencies of molding and casting. Three-dimensional media of scanned fossils are the modern-day equivalent of an age-old practice of molding and casting fossil replicas to assist in preservation of the fossils.

Digitization, sometimes referred to as virtual paleontology, has its roots in the 1980s with x-ray computerized tomography of fossils. This was done to create a less destructive method of

gathering data through cross-sections than by serial-grinding (Sutton et al. 2016). In modern day, laser scanning, computerized tomography, and photogrammetry have become an additional option for researchers that record surface information or gather a 3D image of a specimen. However, destructive methods such as serial-grinding are still the best option for gathering some data. However, digitalization can still be advantageous, as molds and casts would be required before destructive measures are taken, and digitization would be a tool best used to gather a replica cast.

Digitization is broadening the paleontology field, and expanding the capabilities of the data that can be extracted from fossils through more traditional methods (Noris and Butts 2014). However, technology updates much faster than it is integrated into paleontology laboratories. Scanning equipment is not universal to all fossil types, shapes, sizes or quality. This makes it difficult to ascertain the value of justifying expenses for equipment that may not be appropriate for various projects (Kjærgaard 2012).

1.3.2 Responsibilities

Museums must have and maintain a relevance to their audiences that is vital for the institution to maintain their public trust (Macdonald 2006; Lindqvist 2012). This relevance is the focus of outreach programs that the museum hosts for the audiences. Maintaining a steady form of outreach is another core factor of a museum's responsibility, but can also be complicated in terms of establishment and consistency (Krishtalka and Humprey 2000).

One form of outreach for museums can be obtained from the combination of digital media from many different sources that can play a large role in reaching a larger goal than can be met through just the museum alone. Amateur paleontologists have assisted in making strides in progressing the field as a whole, when the proper protocols are followed (Boessenecker 2022).

Amateurs can survey more land than professional paleontologists. They can also provide storage space, rescue fossils that are otherwise going to be lost, and integrate with their local paleontologists through a club or social element to ascertain appropriate behavior when surveying, collecting or other means of amateur paleontology. This idea, however, is still a subject of debate.

Such controversial discussions are in the Society of Vertebrate Paleontology (SVP) letter to not allow amateur paleontologists to participate in any way (Haug et al. 2020). The museum's need, it is said in the letter, to collect the fossil in its formal repository in order to be in a manuscript, so that it may be studied by other researchers and loans for long-term results (Rayfield et al. 2020). It also suggests that it is necessary to accession all specimens into the museum in order to be published, however, this is an on-going debate, and one that digitization could assist with. An increase in utilizing amateur paleontology can open education and accessibility for the public to participate in the museum, which fulfills its stewardship and outreach requirements. Private collections can then be digitally added to the museum's repository, and while the full context of the specimens would not be available, taxon information could be increased.

1.3.3 Restrictions and Limitations

Vertebrate paleontology collections have a unique element of their inherent structure- their specimens are constantly deteriorating and the method of data collection is often destructive. However, the field of museology is making continuous efforts to building a systematic process of increased organization, informed staff, and competent researchers. These efforts can create as ideal an environment for preservation as possible, as well as seamless access to the collections, with the goal of items that are fully utilized to the museum's advantage. This

includes, but is not limited to, not using acidic archival equipment, reducing the specimen's exposure to the elements, and remaining updated on archival preservation research methods (see Figure 1).

While it is estimated that there are over three billion curated natural history specimens, it is also estimated that museums often have less than ten percent of those collections archived and available in a digital format, both to those working in the museum, and to researchers interested in the material (Ellwood et al. 2015; Page et al. 2015). Due to this amount of backlogged information, the need for digital archives has only been increasing, as a means of opening physical space in the lab through a more organized environment, as well as allowing for more specimens to be in the digital archives and available for study. This is in addition to the growing interest to add digital archives in a museum. The documentation and research stage is where the vital identifications of taxa can be fully researched, even if they were collected in the field years before. While preservation is a focus of collections management, decay or damage still occurs within a natural history collection. Digital archives are beneficial to preserve the fossils in their most intact state while still interacting with their images and the associated data.

1.4 Relevant Theories and Practices

1.4.1 Standardization and Digital Practices in Museums

For museums, data and publications must be available to the public in a standardized format to fulfill the accessibility of their stewardship to their audiences. Technology has become advanced enough that different entities have systems and programs to create digital spaces, yet not in a way that is easily shareable between them for exchange and reuse of data without destroying a part of the specimen (Gignac et al. 2024). Research Coordination Networks was founded in the early 2000's, as a means to allow a space for collaboration and communication

between groups of researchers, even between international borders. They can support information exchange, coordination of research, and create standards between interested parties. Programs like this can combine the repository requirement yet still allow for amateur paleontologists to continue to make contributions to the field that leave lasting impact.

Museums creating digital images of their specimens for their archives has been a growing necessity in the field for the last few years, with an increase in the amount necessary for the paleontology and museum fields as a whole. Having a digital database can provide museums more exposure for data collaboration, research connection and education for its audiences through increased knowledge and exposure of their archives using their digital spaces. The accessibility level is unparalleled compared to other elements of data, such as description, photo or video representations. The 3D objects are also malleable, allowing for the researcher to see different angles and thus understand the specimen more than other means of visual representation. (Johnson and Carter 2019).

Institutions that already have integrated protocols for their digital catalogs can assist in interpretation of digital specimens by researchers after field work. The digital imaging itself should have protocol markers for when it is a satisfactory scan, while some imaging technology has built-in features to involve the public in obtaining specimen data as well, to inflate the amount of specimens in the database (Ellwood et al. 2015). Techniques specific to the item or specimen should be taken into account, as well as the size of the specimen. Digital tools should be integrated into the database, such as zoom or the ability to move the specimen around, to best create a usable image with the recipient of the digital specimen. Finally, it is noted that a transfer in jargon from scientific to colloquial verbiage should also be in practice so that the recipient of

the digital data can easily interpret the nature of both the specimen and the data within the digital file.

1.4.2 Funding, Interpersonal Dynamics, and Technological Aspects

Incorporating digitization into an established field of vertebrate paleontology requires a lot of trial and error. This can be daunting given these methods can be costly, constantly require updating, and have bulky equipment (see Figure 1). They also can require a long time to learn, and modern museums are already facing changes of retaining staff and volunteer assistance over a long period of time. One of the largest issues is that of data storage space- adapting the system, cultivating the protocols, maintaining the database, and sharing the data with other organizations (Card et al. 2021).

Unfortunately, another consideration of vertebrate paleontology collections is the likelihood of elderly researchers passing away with collections or specimens in their care that are not returned or possibly lost due to grieving family members or staff without the knowledge of how or when to return the items. The theory is that having a digital archive system will eliminate the need for loans or physical travel due to the information being sent over the interwebs and being received immediately, even through a loan process. It can even expand upon known reputable databases that are grouped by taxon, location or other forms of data. However, the issue of accessibility remains with such an issue, as passwords, methodology of archival practices, and the location of fossil files can still be a hindrance on a digital level (see Figure 1).

1.5 Problem Statement and Scope

The field-wide lack of systematic organization of digitization is partially due to the relatively new technology of digitizing specimens, and the lack of prolonged exposure to the

capacity of digitizing the collection within the museum. Institutions have many considerations regarding changes to protocols, practices and the distribution of resources. In addition to those aspects, issues can be present in the institution between staffing positions and administration that can add an additional layer of complications regarding obtaining the support for digitalization requirements such as technology, lab technicians, funding, or supplies.

Digital archives could be integrated into the wider museum responsibilities and be available to other parties, such as the board members or patrons for approved usage (Ellwood et al. 2015). Digitization is relatively new, and thus data for experimental use in the real world is lacking severely, as well as a system for the data to have quality control. Motivation is a large factor for public interaction with databases within a museum, and that itself is unstudied, or studied rarely.

Best practices that are currently in place do not have standards or documentation when it comes to public participation as well. However, several groups are trying, such as the Citizen Science Working Group, Biodiversity Informatics Standards, and the IDigBio Public Participation in the Digitization of Biodiversity Specimens Working Group. These groups are making a focused effort on combining public participation, digital specimens, and institutions to help streamline data management standardization of protocols. This is needed due to an increase in journals favoring 3D morphological data in their articles (Lebrun and Orliac 2016). This shift requires collaboration between curators and public relations who connect with the patrons of the museum, which can be a complex process but also an area that can be vital to bridge the gap between the public and management, utilizing a standard best practice for digitization of collections.

1.5.1 Systemic, Interpersonal, and Technology Issues

Contribution, collaboration and co-creation are also ways in which citizens can assist with museum's collection expansion and the preservation of fossils that otherwise would not be salvaged (Lozej 2020). This issue is still heavily debated today, due to the advantages such as an increase in volunteers or in the fossils that are available for scanning into the digital systems, there are disadvantages such as an opportunity for citizens to operate and collect data without the guidance of a trained paleontologist- which can lead to a lack of vital context data that connects to the specimens. However, interdisciplinary activism and cross-border networking can greatly increase the knowledge and databases of current specimens, thanks to digitization within the museum's efforts in combining their digital protocols with open-accessibility to the public. Further, allowing for public co-study of digitally available data, there can be an increased relationship for donations of specimens or funding to come to the museum through those connections, thus funding the ability for further digitization.

Whether through citizen collaboration or research networking, digital data collection such as CT scans, photogrammetry, and surface scanning technology has many challenging aspects, especially conforming metadata across platforms. Compatibility between different media types of scanners creates a difficulty in terms of uniformed and seamless sharing abilities, given the different types of systems, software, hardware, and file type that are produced by individual museums (Gignac et al. 2024). A lot of the systems currently in use are not user-friendly nor intuitive, and thus are difficult for interpreters to use and manipulate if they are not familiar with that particular system. The images that are produced may not translate across different platforms, systems, or be too big to transfer across mass-use share files such as email systems.

So-called digital warehouses can host different outputs for researchers, such as text, image, mesh or scans, but this could be costly, not contain the necessary digital requirements for

research, and take a longer time to share the information than if it was being held in the institution itself. This issue will require mass cooperation via researchers and those who build and host the technology to hone in on what paleontologists most use, and to create a system that breaks down the image to a sharable, usable, and intuitive format. The driving force of collaboration is to create a space to advance images and processing of images, create reconstruction elements that are open-sourced, and create a baseline of repeatability. This will increase the sharing and analyzing ability of data and metadata.

This constant change of technology must be reflected on by the financial backing of knowledgeable individuals. Prioritizing digitization can only be built into the practices of museums through an understanding of what the current initiatives surrounding digitization are, both in the national and international museology field (Vollmar, Macklin, and Ford 2010). This need for collaboration hinders access by all of the community involved to ensure best practices to know the technological requirements to best protect and preserve the collection (Card et al. 2021).

Open access standards and collaboration also needs to extend to a global and international basis. Policy and procedures need to be instilled to fully open the access of collaboration between institutions. The White House Office of Science and Technology Policy Nelson Memorandum must align with open science standards across other nations and thus create a NSF's 2022 FAIR (Findability, Accessibility, Interoperability and Reusability) to enhance interpersonal ability and access (Wilkinson et al. 2016). Other efforts such as NoCTURN, the Non-Clinical Tomography Users Research Network, and Open Science (FAIROS) Research Coordination Network, has goals to establish initiatives for museums that must collaborate and be connected with other institutions and protect against security threats and

abuse of the systems by setting standards across borders and institutions while also creating guiding principles based on best practices (Gignac et al. 2024). This will require many different experts and insights to create, build, test, and evaluate the data management software and how they can be translated across to different institutions and internationally.

1.5.2 Research Significance and Purpose

Digitization in general, is to secure a quality copy of a physical specimen that can be easily accessed with all its data intact. The organization of data in the museum is vital, as this is where the study of the specimens is fully realized from the other vital element- maintained pristine context while gathering the specimens in the field (Page et al. 2015). This thesis is aimed to evaluate the best practices that can be determined on a field-wide basis by surveying individual museums on their current practices, individual challenges that will be compared for similarities, difficulties that can be compared for solutions, and what forms of 3D data is used to gather digital data. It will evaluate resources such as funding, staff, storage, equipment, security, connections both social and research-based, and if they are open-source or not. Through the answers of the survey, similar and differing patterns of practices will be evaluated with a discussion of short-term and long-term directions for museums to establish possible standards of protocol on how to begin building best practices within their institution.

Chapter 2: Literature Review

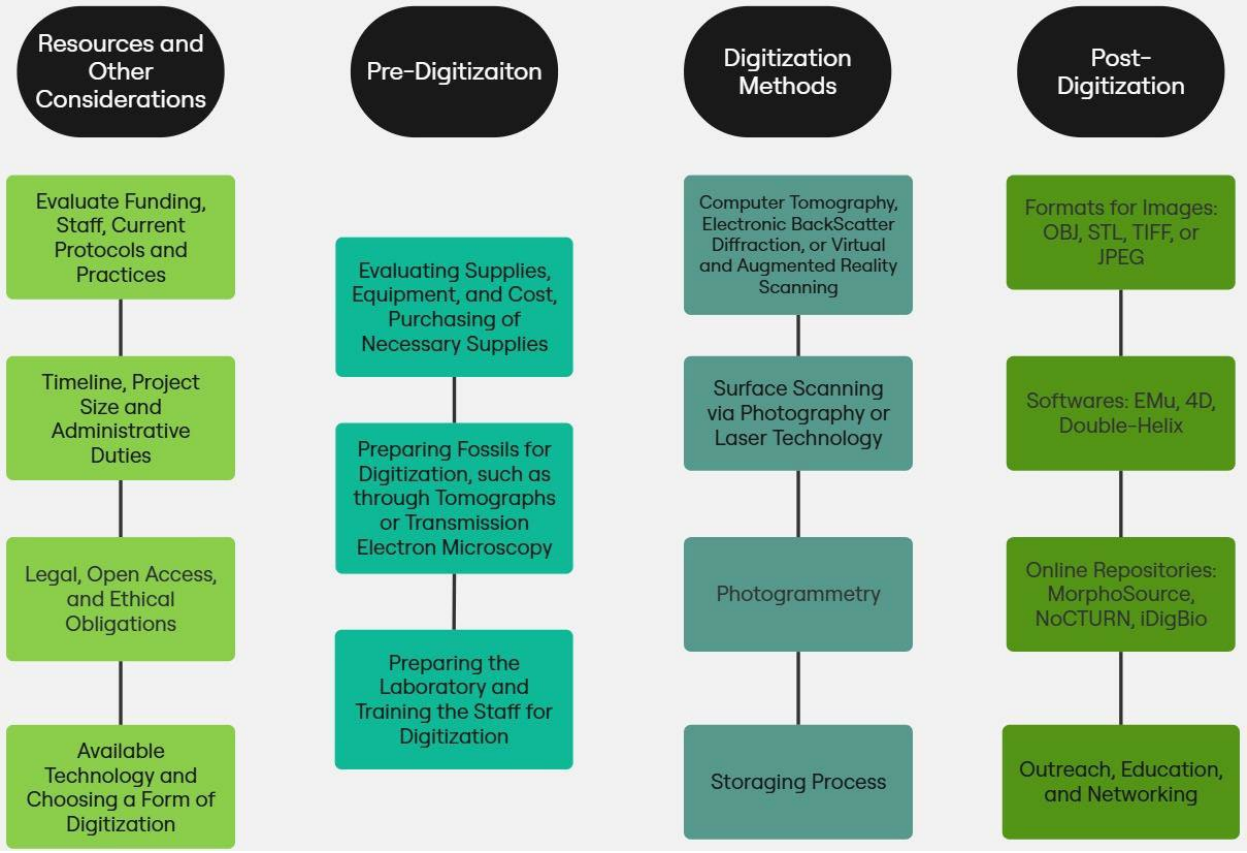

Figure 2. Process of Digitization.

2.1 Museum Resources and Practices

The American Alliance of Museums [AAM] (2024) represents the museum field in the United States and also defines standards as accepted levels of achievement and behaviors for museums on a nation-wide basis. The obligations of museums are named Core Standards, and must adhere to multiple areas of responsibility, such as public trust, collection stewardship, financial stability and facilities, and risk management. For collections stewardship, specifically, the AAM notes that an institution must legally, and ethically manage their documents, develop their collections and research their archives with the goal of open access for their audiences. They also assist with guidelines and considerations regarding digitization, as widespread accessibility of digital archives, the networking aspects of digitized collections, and the ethical,

legal and financial responsibility the museum must consider to properly digitize their specimens are complex and layered aspects of a museum's duties (see Figure 2).

A study performed by Ana Vollmar, James A. Macklin and Linda S. Ford (2010) from Harvard University focused on specimen digitization, and the challenges and concerns in natural history collections. After an international survey with 200 respondents, the main barriers that were found were a lack of museum resources- such as funding, staff responsibilities and time availability. Cross institutional and geographic limitations were also named as a challenge, along with the jurisdiction of fossil data. Their conclusion was that a specialized form of socialized coordination is required to increase the resources for digitization of natural history specimens.

An article by José M. Valle Melón et al. (2019) discussed the use of new web technologies for the analysis, preservation, and outreach of paleontological information. They outlined responsibilities and rights of the museums to provide resources for digital practices such as establishing agreed upon parameters between creators, and creating an established protocol for communication between data structures. The results of the article were to define various management elements such as research files that were in analog format but not compatible with digital standards. This, Jose et al. stated, increased the risk of a loss of info and data. Their solution is to upgrade the digital management protocols within museums to increase the protection of both the analog and digital resources in the museum.

John A. Cunningham (2021) wrote The Use of Photogrammetric Fossil Models in Paleontology Education for the journal Evolution: Education and Outreach. They provided volunteer questionnaires completed by 28 students in five statements and fifteen free-text questions on how the digital models increased their interest in the presented fossil information using photogrammetry. This form of digitization- discussed later in this chapter- can be

advantageous for educating patrons given its ease of creation. Museums have digital elements of their collections available online, and the survey performed by Cuningham noted that the students felt they were more engaged with the added use of digital aspects of their museums. They noted limitations, however, that there was a lack of digital details that made it difficult to maintain interest- such as scaling or an explanation of digital features in the presented material. Despite this, Cunningham states that museums who place resources into digitalization can utilize that material to fulfill many of their duties to their audiences.

Museum resources and practices are a vital piece of establishing best practices with regard to digitization (see Figure 2). With organizations already established such as the AAM (2024) that have defined and accepted standards in place, creating established protocols and practices on a nationwide- and potentially worldwide usage- is a crucial benefit for museums to utilize. As Vollmar, Macklin, and Ford (2010) researched, resources in museums on a global level are a critical barrier for increased digitization.

However, 200 respondents is a large and overwhelming starting point for researching which best practices to begin putting into place but is a good source for understanding how large this issue really is on a field-wide basis. Valle Melón et al. (2019) have a good starting point in how small efforts by museums can go a long way toward understanding how these issues begin in individual museums, creators, and communication. Additionally, Cunningham (2021) notes that small efforts of digitization can be unitized to the best of the museum abilities while larger and more complex issues are being studied for a more long-term and field-wide solution. My thesis aims to add to these sources, as asking collection managers for feedback on their institutional resources and daily practices along with their current digitization methods is a core solution for increasing digitization.

2.1.1 Funding and Staff

Some researchers are exploring solutions to resource issues. Robert W. Boessenecker (2022) conducted a case study regarding amateur collectors in vertebrate paleontology, and how they can be a critical benefit for institutions to not only maintain their current collections, but to expand their abilities to study the field of paleontology that they may not otherwise be capable of. The survey supported the hypothesis that fossil collections benefit greatly from the inclusion of amateur paleontologists assisting experts in the field, by being able to mobilize faster, have a greater amount of fossils found due to the number of volunteers, as well as extensively helpful in the laboratories of paleontology collections through being treated professionally. However, there are risks involved, such as citizens contributing to conflicts between opinions or practices between amateurs and the institutions.

In addition to these considerations, Lucas Siqueria Rodrigues et al. (2023) from the Humboldt-Universität zu Berlin wrote a study that focused on technical preparators and virtual paleontologists. The focus group sessions discussed workflows and potential solutions for challenges. These, mainly, contributed to a lack of understanding in what staff members were finding in digital images, or a lack of direction with the technology used to create digital images. Additionally, the work is “experience driven” and thus they concluded that fossil preparators' duties are more challenging due to the design of the position itself, and require more rigorous training to fully perform their duties long-term.

Regarding one of the most vital of museum resources- funding- Katja Lindqvist (2012) wrote that institutions can receive funds from both the public sector, such as government allocations, as well as private funds, such as donations from individuals or companies. She notes that there is a complex and individual aspect to how museums balance their incomes and

expenditures, which creates their standing in the main categorical expenses- facility costs, assets and activities, as well as personnel costs. Lindqvist also mentions external expenses along with the internal- competition of both in-industry and out, stakeholders interest, and the concern of remaining relevant to their audiences, politicians and board members. She concludes by discussing how museums can sometimes not change course in how they allocate their funds when balancing relevance, stakeholders, and obligations, at least not in the short-term.

Resources do not always just include physical aspects for an institution. Paul F. Marty (2008) conducted a survey to 1200 visitors via nine online museums to access the digital resources and their connection to successful networking, both before and after physically visiting the museum. He states that it is a necessity to understand the relationship between digital resources and how they are both understood and utilized, as technical considerations and the mechanics of digitizing collections can create unknown use of those resources by both visitors and research networking protocols. The results of the survey were positive- users exhibited strong opinions regarding digital museums, and museum professionals can incorporate digital databases to strengthen strategies of engagement and interest.

Museum resources are an individual aspect of institutions due to each having their own stream of income- from public government to private stakeholders, to individual needs such as location and audience, to how they manage the technological resources for their audiences and research opportunities. Lindqvist (2012) noted how funding is both vital and complex, driven not only by unstable income methods, but also by temperamental expenditures. Marty (2008) added to this aspect by discussing that these considerations are not only physical in a museum, but also digital. Boessenecker (2022) and Rodrigues et al. (2023) studied possible solutions to another major aspect of resources- staffing issues- however, both admit that the issues are not easy fixes.

My thesis explores these elements of resources as well, to discover what structures within institutions are being met and what institutions are currently doing to circumvent, or even solve, these issues.

2.1.2 Best Practices in Digitization

Gil Nelson and Shari Ellis (2018) wrote The History and Impact of Digitization and Digital Data Mobilization on Biodiversity Research, which describe how multiple organizations around the world- the National Science Foundation's Advancing Digitization of Biodiversity Collections in the United States for example- created a massive digital database for museum specimens, which led to an increased need for data quality via procedures, research methods, and cultivating accuracy, and completeness. These are the main challenges proposed by the article- that best practices are not established and the quality of digital data must be improved through them. Due to a lack of data quality, there are a large number of misunderstandings and misapplication with fossil data that occurs in the field, which has outstanding consequences when translated to research, education, and public outreach. The article suggests a greater amount of focus in developing well-ordered and fully documented digital archival systems for both digital copies of fossils, as well as the contextual information that surrounds them.

An article by C.R. Marshall et al. (2018) describes how paleontology is generally shaped by large-scale information from the fossil record, and discusses how the data used to be prepared by hand. This led to paleontologists needing to sort out what information was most vital to share given the physical limitations of the staff. However, due to the rise in computers, these practices adapted to allow for databases to be expanded exponentially on a field-wide basis. Databases such as the Paleobiology Database houses over 194,000 collections sites, 371,000 taxa and 1.37 million fossils, which allowed for over 317 publications. However, this database does not reflect

the full ability of comprehensive fossil data in the US. The article states that when computers became integrated into the field of paleontology, standards and protocols were attempted to be set in place to utilize the benefits while minimizing the challenges involved (see figure 1). However, this was done with minimal success. They call for a secondary type of revolution within the field- to set practices and protocols to take advantage of the digital tools available and expand the field in the digital age.

Stephan Lautenschlager (2016) wrote an article regarding his approach for changing methods and techniques for digital restoration. He discusses how the process of fossilization can create a range of specialized difficulties in morphology with various cracks or fragmentation. These difficulties can be restored through the use of digital tools, including restorative techniques for fragmented fossils- he theorizes that these methods can even be automated. He states that these methods are already used in paleoanthropology, but have yet to be incorporated on a wider scale of digitization. They state that digital methods are tools that can be applied to fix complications that are deeply engaged in the field of paleontology- that digital tools can be utilized and applied to further the field beyond what was available in the past- where morphological data, research outreach and education can greatly benefit.

Best practices for paleontological labs can be difficult to access due to individual grants, physical space and staffing abilities. In essence, each collection and institution is highly individualized regarding their needs (see Figure 2). However, field-wide practices such as context database protocols can be established through collaboration, as Gil Nelson and Shari Ellis (2018) discussed. C.R. Marshall (2018) also noted that through the technological age, the collaboration ability by many institutions are enhanced greatly, as are the results of that collaboration. Both sources point out that this is merely a beginning point of paleontology and

the utilization of digital tools. Stephan Lautenschlager (2016) gives an example of how digital tools can be vital for best practices, how challenges that the field has been facing for decades can be remedied and benefited from collaborating on a solution. These three articles note the issues of a lack of established best practices, however, they do not go into detail about how to solve this issue. While it's important to understand the challenges that are faced when establishing best practices, my thesis focuses on the daily current practices of institutions, and how we can utilize the sources that study how and why there is an issue with digital practices to better create a collaborative and established set of protocols.

2.2 Ethics, Laws, and Globalization

Ethical, and legal requirements can be a long and arduous process. Dyani Lewis (2019) wrote The Fight for Control Over Virtual Fossils on this topic. They analyzed over 200 paleontology papers from 2017-2018, with 122 describing digital objects. Overall, they note a lack of acknowledgement in research papers regarding who owns the physical and digital specimens. There is an absence of clear community standards, and that even if the National Science Foundation requires an outline of data management, the practice of enforcement is lacking at best. Given the rarity of paleontology specimens, the lack of ethical guidelines on a digital scale leaves the decisions to the institution- thus creating a fear of losing control and developing a lack of clear-cut consequences of ethical violations for digital specimens.

Donat Agosti and Willi Egloff (2009) noted in an article regarding taxonomic copyright that taxa and their information are public domain, and can be utilized in research whether or not they are in copyrighted publications. Legally, copyrighted work is defined in this article by examples such as articles, photographs, sketches or forms of secondary publications of primary data. One example of primary data would be paleontological specimens. Taxonomic information,

therein, is not subjugated to copyright, it is instead considered public domain. It, by its nature, is considered stewarded data and is included in public access and in open-access practices. Digital data is a mix of both primary and secondary data, and thus is unclearly defined legally.

Additionally, Gil Nelson and Shari Ellis (2018) wrote a paper that describes multiple databases from various countries and organizations, including the National Science Foundation's Advancing Digitization of Biodiversity Collections in the United States of America. These initiatives in digital data have led to a rise in the use of globally available digital data in the scientific research community. They state the ultimate goal of integrating specimens is to link specimen records to every derivative context possible.

Paleontology is inherently a collaborative science. Vertebrate paleontology even more so, due to the type of specimens that are researched. There are clearly written guidelines for ethics and legal practices as outlined by Lewis (2019) and by Agosti and Egloff (2009) for physical specimens, digital specimens are still in a limbotic state. Due to the overarching goal of connecting context for the benefit of the field as outlined in Nelson and Ellis (2018), ethical and legal outlines of behavior between institutions is a core challenge to overcome (see figure 2). These sources outline the issues involved, but not what solutions are being explored. My thesis, through my survey of various institutions, will focus on what areas institutions are experiencing on a daily level, and how to possibly move forward to create more cohesive legal and ethical practices for the benefit of globalization.

2.2.1 Public Trust, Stewardship and Open Access

The American Alliance of Museums [AAM] (2024) lists public trust underneath their ethical core standard for museums. Public trust is vital for institutions, as they hold the public stewardship of fossils, data and context for the global commonwealth of prehistoric knowledge.

The AAM notes that public trust must uphold its accountability to its community, and derive its resources for the benefit of its audiences. Additionally, it must be diverse and inclusive in its public service role, with education the main focus to its physical and intellectual access. The museum must maintain adherence to the ethics and legal outlines guided by the AAM, as well as state and federal laws. These are the standards to maintain public trust- the trust that the public has with regard to the institution.

Discussing the connection with laws and stewardship, Thomas G. Davies et al. (2017) states that, though there are many digital datasets, available via published studies, many underlying digital data is not available, or has a barrier to verification and reproducibility. This decreases the likelihood of the reuse of data for additional research. They also note that this is due to there being a lack of agreement or policy on the amount and type of data that should be made available in some journals and other published studies. The principle of open data is under mandate by a majority of funders and publishers, however, the ownership of digital data remains unsolved between the researchers, funders, museums and research publishers. This stagnates open access and muddles stewardship of the collected data by creating a controlled environment of a reluctance to release full datasets.

John A. Cunningham (2021) argues that open-access is expanded through the incorporation of digitization. He states that through the use of photogrammetry (discussed later in this chapter), educational tools are enhanced through this form of digitization. He does acknowledge the challenges of using digitization for education- such as a lack of scalability or explanation in some features- but that ultimately, digital fossils can play a vital role in the education of paleontology. This includes remote education, studying rare specimens in a safe

environment, providing teaching material when other types are unavailable, and providing a fair and equal amount of education opportunities.

Public trust, stewardship and open access are core responsibilities of institutions. The AAM (2024) outlines these in terms of physical and established collections, however, it does not outline the digital aspect of collection management, and allows for the need of individual adaptations of institutions (see Figure 2). However, digital aspects of public trust, stewardship and ethics must also align with the AAM (2024) once established on a field-wide basis. Davies et al. (2017) notes this through the lack of reuse in digital aspects of published research. The principle of open access is intact with physical specimens, but not yet through digital data. Cunningham (2021) outlines the many benefits of establishing these protocols on a global basis, once these elements are implemented. My thesis will explore how museums are navigating the current lack of digital guidelines for possible similarities. This will be done with the hope of outlining a next plan of action regarding the fulfillment of the vital roles of public trust, stewardship and full open access.

2.3 Technology and Tools for Digitization

2.3.1 Pre-Digitization Techniques and Equipment

Preparing for digitization can be a stressful and complicated decision for an institution. Talia S. Karim et al. (2016) described how there are many different steps between an institution deciding it would digitize, and beginning the process of digitizing a collection. She noted the various decisions that are involved in deciding what type of digitization would be used, the costs involved, the equipment such as cameras, lenses, software, hardware, and lighting equipment. These types of physical equipment can be considered a long-term investment, especially as digitizing an entire collection can take years.

Adding to the discussion, Martin Rücklin et al. (2024) discusses the process of preparing a type of digitization called tomographs, which will be described later in this chapter. To prepare the fossils for this form of digitization, collection staff must polish thin sections of a fossil to capture images that are then assembled into a data set and interpreted as a 3D model using software programs. This, however, is a destructive form of preparing fossils, yet it is representative of the type of options that researchers must consider when deciding what type of digitization they will be using.

This aspect of digitization is constantly expanding, which is a benefit for both cost and individual needs, but presents challenges for accessibility and transferring data. Louise Zylberberg and Michel Laurin (2011) did a study on fossil study via transmission electron microscopy. This study focused on testing if demineralization treatments for electronic microscopy could affect the organic residue in fossil bones. The results showed that the fossils are preserved enough for staining, and thus can be studied through this method of digitization.

These sources focus on the pre-digitization phase of preparing fossils. This stage can be one of the most important, as it determines the remaining process of digitization. Deciding what equipment is needed, what type of equipment, the amount of destruction involved with the fossils, as well as the type of preparation and the budgetary allotments can be challenging for a museum to decide. Karim (2016) notes the technicalities that are involved with the pre-digitization that some collection managers may not instinctively think of, while Rücklin (2024) and Zylberberg and Laurin (2011) represent different routes of preparing the fossils for being digitized (see Figure 2). These decisions and challenges are represented in my thesis by questioning the institutions of how they digitized their collections. Understanding pre-

digitization decisions is an important aspect of understanding the digitization process and how to establish best practices.

2.3.2 Digitization Methods

Heinrich Mallison aus Tübingen (2007) wrote a dissertation discussing the benefits of computer tomography (CT) scans with fossil digitization. The creation of virtual specimens from their physical specimens have been revolutionary from the physical molds and casting in previous years. This is due to being able to penetrate beneath the top layer to be able to scan the internal structure of the skeleton. However, this comes with a downside of producing a large file size, which can result in losing accuracy if reduced via meshing practices. He states that this can be remedied by cropping all unnecessary extra or empty space that is included in the exported format. These smaller types of files can be easier to handle and assist with accuracy issues. It can then be easier to be copied, shared and stored.

Additionally, Moreno A. Otero et al. (2020) wrote a paper regarding the three-dimensional image surface acquisition and its role in vertebrate paleontology. This review is focused on three-dimensional (3D) surface scanning of fossils. This method captures images from the fossil on a surface-level basis- a computerized format of physical molding and casting techniques. Image surface scanning incorporates various types of hardware and software- from portable or non-portable scanners, cameras, imaging software and a transition to shareable contents. There are varying degrees of differences between them, such as scanning times, post-processing times, costs and image resolutions. He mentions this type of digitization is focused on image acquisition.

Overall, CT Scanning appears to be one of the more prominent forms of digitizing vertebrate paleontology specimens. David Blackburn et al. (2024) presented a study of the

impact of how to preserve specimens by transforming them into 3D images through an online network called OpenVertebrate Thematic Collections. The goal of this study was to build a community of various forms of digital archiving, including CT Scanning, Surface Scanning, Photogrammetry and Structured Light Scanning efficiency, as well as analyzing the data archiving and accessibility vitality of such a program. Through 16 initial National Science Foundation awards, 18 institutions and 290 people, the study showed that 505 loans between 50 international institutions interacted through the program. This benefits multiple global institutions that otherwise would not have had specimens to utilize for their research programs. This article also shows how collaboration through networks can create a much larger impact when institutions work together.

Another form of digitizing specimen was published by Seung et al. (2024) from the Research Institute of Basic Sciences in South Korea. The authors outlined their protocol for Electronic Backscatter Diffraction analytical techniques. This form of digitization can be used by different fields of geology due to the mineralogical properties such as grain size, shape and boundary information. It can also be used with fossilized bone due to the development of new detectors. Choi et al. (2024) designed the project and wrote the protocol, discussing in detail how this can benefit vertebrate paleontologists by having an additional source of digitizing data. However, the process does pose a risk of damage during preparation, as the specimen\ must be coated in non-removable epoxy resin. However, the actual analyzed surface of the data is noted to have no damage, if the beam is correctly calibrated. While this form of scanning digitization is still being developed and studied, it can be an option for curation managers when deciding which type of digitization to incorporate in their collections.

Scanning machinery such as CT and EBDS described above can also be used to expand on preserving the specimen, however, Cieri et al. (2021) wrote a manuscript that describes Virtual and Augmented Reality technologies that utilize the 3D scanned images in a new way. Where Blackburn studied the impact of 3D preserved images through an open network, Cieri et al. explores that technology when applied to VR applications. Augmented reality projects the virtual specimen in a real-world environment. This could enable scientists to have access using open-source software and examine their specimens in a specific and technologically revolutionizing format to better study morphology of vertebrate paleontological specimens. However, this manuscript does acknowledge the difficulties of obtaining the equipment necessary for this technology, which is funding and longevity of the technology, along with the open-access and shareability of the presented data.

These sources focused on the type of digitization methods- surface scanning via photography, surface scanning via laser scanning, and in-depth scanning using computerized tomography scanning (see Figure 2). The benefits of these formats is the various amounts of data and start-up barriers to obtain a digital image of a specimen. This saves the fossil from being damaged from traditional physical molding and casting techniques. However, various equipment and sizing requirements can be an issue, as not all fossils can be scanned in the same format. My thesis focuses on what type of digitization is being used to ascertain if there is a common link between the available software choices, and the practical, realistic and daily actions of collections staff.

2.3.3 Post-Digitization Formats, Software and Online Repositories

2.3.3.1 Formats

While digitization is the process of transferring physical specimens to digital, the process does not stop there for institutions who wish to share their data with fellow researchers and the general public. Just as with the process of digitization, the type of formatting can be complex for collections staff as well. R.L. Cieri et al. (2021) wrote a paper that discusses how digitally cultivated specimens have created a new platform of interaction, but that formats can be difficult and unintuitive to interact with. Common types of 3D data files to work with are OBJ, STL, and FBX. The challenge with these formats is that they can differ in the information they have regarding the 3D model. For example, STL only describes the surface geometry, while FBX files include colors, textures, and materials. However, they suggest that one solution can be introducing Virtual Reality and Augmented Reality to fossil study- the ability to enhance the information kept in STL, OBJ and FBX files, among others. They note that hardware for VR and AR is becoming more affordable, with open-source software in development.

Due to these issues, there is a considerable amount of effort to solve these issues. Thomas G. Davies et al. (2017) proposed a minimum standard recommendation list for 3D data publication. They suggest having designated export file types- TIFF, JPEG, BMP- to facilitate a more streamlined practice of open and free-to-view software. This is due to metadata information not being able to include the full details of a scan, copyright issues, and repository storage capabilities. Factors of consideration include file size, texture information and color type must be considered when choosing an export format. However, they state that currently, there is not an ideal file type currently available. They note that as of now, OBJ or PLY seem to hold the most amount of 3D data for specimens, but that more of an effort for data visibility through 3D export formats.

Davide Delfino and Valentino Nizzo (2018) wrote for the Proceedings of the XVIII UISPP World Congress on the topic. They note that JPG, TIFF, and PNG are the most common and simple formats for overall 3D purposes, but add that TIFF and PNG files take up more memory space, while JPG provides the lowest quality but is light on memory space. TIFF and PNG have the higher resolution- and therefore quality.

Formats in digitization are one of the most important aspects to consider, as the data involved in each one is different and can be lost if transitioning between formats. Cieri et al. (2021) suggests introducing new technologies into the issue such as VR and AR, while Davies et al. (2017) suggests a minimum standard of formatting on a field-wide basis. Delfino (2018) suggests the same, with TIFF and JPEG being the most mentioned in the literature. However, these have different abilities of storage, and thus, can be individually needed by various projects (see Figure 2). Ultimately, this area needs a lot of study, and my thesis notes what each museum is using, to assist in creating a baseline of best practice standardization.

2.3.3.2 Software

Mark D. Uhen et al. (2013) wrote an article regarding the transition from card catalogs to computers, and the impact of evolving vertebrate paleontology databases. They note that in-house software within an institution is a "stand-alone" database, relying on its own server within the institution. These formats of data management have the benefit of having open-access while allowing the museum to have control over the accessibility of reproducing the material involved. This would include both researchers and citizen enthusiasts alike.

A study performed by Srinivasan et al. (2009) also supported the use of online catalogues in a natural history setting. They compared two user groups- one at a high school level and one at a graduate school level- and concluded that museum online catalogue systems must adapt to a

more digital- level of archival practices. The ability to open access to their audiences increases exponentially with online programs, which are facilitated with catalogues that allow for the careful management of data and information of specimens. They concluded that tagging and local description were not a form of engagement for the student involvement, however, images, descriptions and contextual information were key for engagement, and through the databases options, students noted how they desired a deeper connection with material and experts through the museum's database that is available to the public.

However, not all software programs are able to be utilized across all institutions. Elana C. Carpinone (2010) wrote a thesis on this topic, that to a degree, some software can be useful on a field-wide basis, but not as a whole solution to every collection department. She notes that there are a number of factors to consider, from the individual category needs of a museum, to the number of objects, system of archival protocols, as well as processor speeds and administrative concerns. Additionally, a museum must consider the financial health of a software or technological company. Additionally, she notes the start-up costs can be high, ranging from $800 to $16,000 depending on the package, system and company that are chosen for use. She concludes by stating that collection management practices are continuing to evolve, and institutions should consider all aspects before making a final choice.

One such example is that of EMu Collections Management Systems (2024). EMu is an archival software that facilitates the in-house storage capabilities within an institution between the digitization of an object, and the out-of-house connection between researchers, public engagement, and global outreach. María Consuelo Sendino (2009) wrote how this particular management system is best for natural history collections- how it manages and exports data and standardizes the documentation of context for the museum using it. The goals of this software are

to inventory, catalogue, manage loans and track context and external movements of data, among others. The mechanics of this software are more aligned with how paleontologists must manage their catalogues to best maintain their archival practices.

Collection management software is a vital part of vertebrate paleontology archival digitization, as once the specimens are created in a digital space, they must be connected with their context, as Srinivasan et al. (2009) noted. This connection, as seconded by Uhen et al. (2013), not only houses this irreplaceable information within the institution, but also enables the data to be controlled by the staff, shared with colleagues, as well as to the public. While Carpinone (2010) notes that the process of choosing and establishing a software is extensive and time-consuming, museums must make an informed and careful choice regarding how they wish to store their digitized collections (see Figure 2). Sendino (2009) notes how the EMu (2024) software collection has come a long way, and is a viable option for museums, however, the issue of longevity still remains. This thesis will explore how museums are adapting to their software issues, if there are backup plans in place, and what software museums are currently using.

2.3.3.3 Online Repositories

Out-of-house repositories, community efforts, and resource use are also on the rise for modern-day collection staff. Boyer et al. (2017) wrote an article on their design of Morphosource, a repository available to institution's collection departments on a digital platform that utilizes crowd sourcing for maximum open-source datasets. They note the challenges of long-term governance, utilization of the community- such as user error- for a more streamlined experience, as well as supporting large amounts of digital storage. They discuss how MorphoSource creates the digital space for raw datasets of multiple sizes, how privacy of data can be controlled by the author of the data set, and how it creates an expanded knowledge of

taxonomy via both researchers and enthusiasts. They conclude by stating that this repository also collects statistics on their data use. While MorphoSource is not a final or cure-all solution for digitizing archives, it can be a viable option for current curation staff in view of other digitization issues that take longer to fix, such as legal or storage space considerations.

Another resource actively working toward systemic issues is Integrated Digitized Biocollections (iDigBio 2024). Gil Nelson and Deborah L. Paul (2019) wrote how this organization is a group that emerged from current museum-based professions, along with other biocollection colleagues. Nelson and Paul discuss how this foundation focuses on data generated by the general public, non-federal museums and academic collections to create datasets. They dictate that it has 29 million specimen-based media records from 1600 datasets across 700 collections and 400 institutions. It also enhances morphological data and they have a goal to standardize data models and cyberinfrastructure. Additionally, they work with the Smithsonian, who have one of the largest digital collections in the United States of America.

Another community effort to build standardization in digitization is NoCTURN (Non-Clinical Tomography Users Research Network 2024). This organization combines the communities of educators, researchers, and industry stakeholders to collaborate on how data is created, managed, and organized on an international basis. They state that their goal is to expand on the current practices of how datasets are managed, and focus on expanding the four core elements of digital collections- findability, accessibility, interoperability, and the increase of reusability. They have goals for standardization through discussion and experimentation through their individual facilities.

Efforts such as MorphoSource (2024), iDigBio (2024), and NoCTURN (2024) all highlight the key component of this thesis- there is a lack of digitization standards on a field-

wide basis in vertebrate paleontology collections, and there is a concerted effort to correct these issues, both in the short- and long-term (see Figure 2). Boyer et al. (2017) discusses these solutions in terms of a repository, while Gil Nelson and Deborah L. Paul (2019) as well as NoCTURN (2024) are approaching solutions from a community-base. All of these efforts are an excellent aspect to forging digital standards for institutions to use as a guideline for their practices, and this thesis will explore what avenues the respondents are utilizing. In order for both out-of-house repositories and community-guided efforts to be successful, information must be gained from institutions on exactly how much of an impact these efforts are having in the collections themselves.

Chapter 3: Methods

3.1 Survey Protocol

This study was constructed by researching the intersection of digital media, museum practices and the growing technological adaptations and advances within the vertebrate paleontology collections of natural history museums. The specifics of how these subjects interact with each other is a complex and highly intertwined system of operations between multiple fields of study. A myriad of potential influences were taken into consideration when forming this survey. These include, for example: differing perspectives of employed collection managers, funding availability of their departments, laws at the state and the federal level, access to tools, and the status of various digitization technologies in the industry. The questions within the survey were designed to best ascertain the multiple layers of factors that contribute to a museum digitizing its vertebrate paleontology collection.

The subjects were the museums and institutions that have collection managers in their employ who work closely with the vertebrate paleontology collection of that institution. The

specific discipline of vertebrate paleontology was chosen due to the combined interests of the thesis author and their collaborators. With the subject, target recipients, and questions for the respondents decided, the surveys were sent out via email and the responses were received in the same style. The questions were open-ended to encourage a style of long form narrative answers of the respondents.

This thesis utilized qualitative research protocols via survey using an Action Research Methodology. This type of research focuses on context through participatory actions, with an emphasis on knowledge gaps and how to change daily practices (Oosthuizen 2002). This format was chosen based on the nature of the thesis- that we have knowledge of the benefits and challenges of digitization but lack contextual realistic implications of individual vertebrate paleontology collection departments. The survey was sent out to natural history museums or university-level institutions that were selected due to having vertebrate paleontology collections. Both were included in the available pool of availability for surveys, as paleontologists work through both types of laboratory environments, and the goal of this thesis is to mark similarities and differences for digitization on a field-wide basis, which includes both paleontologists that work in museums as well as paleontologists who work through university-level institutions.

The participants that were invited to respond to the survey were both museums and institutions that have vertebrate paleontology collections. They were known to have general and various states of digitization means within their resources, but the specifics of their best practices and the states of their digitization projects were not known. Other factors were the type of museum or institution, such as those whose specimens were considered public domain, and others who are classified as being privately owned. The variety of invited participants would

help cast a wide range of knowledge on the results of the survey that would reflect the vast differences that museums and institutions must factor in to create field-wide practices.

In total, eleven museums and institutions were sent the survey, and five responded back with their experience in the implementation of digitization within their collection. The surveys were returned with the intent to ascertain and subsequently summarize the scope of concerns related to this topic, explicitly from the perspective of the professionals who grapple with these issues. In turn, a goal of the project is to contribute to ongoing conversation towards resolving these issues within the fields of both museology and paleontology. The methodology and survey format were chosen due to the actionable steps that must be evaluated by researchers to better implement change in how paleontologists and museums establish best practices for digitization. The questionnaire style was chosen based on the highly varied nature of information being requested while simultaneously striving to keep the survey questions concise and simple to maximize likely participation. This format was chosen with consideration for curators and collection manager's schedules and amount of responsibilities.

The contextual results of this thesis will be applicable to not only the vertebrate paleontology collections that respond to the survey, but will be applicable on a fieldwide basis of paleontology, or even other types of collections within museums. Paleontology collections can have different circumstances- some have a variant in the number of specimens in the collection or have a difference in funding availability due to public interest or donations- making funding for vertebrate paleontology larger than others due to popular types of specimens. The size of the specimen storage can be impacted as well, due to the size of vertebrate specimens. This can translate into the needs of digitization, as various forms of technology can be needed for micro specimens than for massive specimens. Research opportunities and other museum aspects like

exhibit design can also create a greater challenge for digitization due to how specimens are assembled and displayed in the museum. These and additional factors can affect how each museum can apply their own format of digitization. These differences will be considered and explored in this thesis. They are vital to understand in order to properly assess what aspects of digitization can be implemented on a field-wide basis, or which aspects require a deeper study to understand properly. Ignoring these factors create a gap in knowledge of what museums consider when creating their best practices in their collections department.

3.1.1 Survey and Question design

The following survey questions were sent out with the intent to allow the collection managers to give a full and encompassing viewpoint of their experiences in their respective collection departments. The first question, "To the best of your knowledge, what proportion of your museum institution's funding comes from public versus private sources? Is your institution considered a public or private institution?" was chosen to establish what type of institution it is and where one of the most important resources -funding- is sourced from for this individual vertebrate paleontology collection. It was worded in such a way as to establish a baseline of which type of institution was private or publicly supported. Institutions can receive different amounts of support from different avenues, which can impact digitization efforts. The aim of the question is to ascertain if there is a possible link to private or public support equating to more availability for digitization. Some institutions can be a blend of private and public support, however, it is still an important establishing question to ask for understanding the context of resources available to the collections department.

The survey's second question on the survey, "How many specimens are in the collection that you are responsible for? How many are available on a digital repository?" was chosen to

also establish a baseline of how many specimens make up the whole of the collection versus how many have been digitized and are available for research or public access in a repository. The question was worded in such a way to directly ascertain the number each institution is working with in their collections, and to compare it to how many they have digitized. This question aims to evaluate an individual institution's ability, goal, and execution of digitization projects, as well as gain an understanding of what the current situation of the collections department is. This is also a way to best compare different institutions to gain a sense of the larger picture of digitization in vertebrate paleontology collections as a whole.

The third survey question, "How does having a digitized collection connect to the museum's mission and vision statements? In what forms were the specimens digitized? (scanning, photos etc.)", is to connect the digitization efforts with the stewardship, public trust, legal, and ethical duties to their audiences and the global commonwealth of knowledge. Mission and vision statements are important titles for the goals and fulfillment of obligations in institutions and were worded in such a way for clarity of understanding. Additionally, the form of digitized specimens is vital to understand for the study, as it creates data for how vertebrate collection departments create digital copies of their specimens. This aspect is a core study of this thesis, as the results can help establish a process for which collection departments can implement moving forward in their best practices. The term "form" is a loosely defining aspect, which encompasses all aspects of digitization. This phrasing was chosen to create an open-ended inquiry into how the institutions chose to digitize specimens, which can be vital data for further incorporation of a standardization of best practices. This question aims to establish what institutions have done to digitize their specimens, while also asking why they chose to, and how digitization will fulfill the core duties they have to the public.

The survey's fourth question, "What programs or software does/did your museum use to transition specimens to digital archives?" is another core question to this thesis. Institutions who add digitization must make decisions on how to utilize their resources through a variety of programs and software to complete the digitization process. Understanding which ones were chosen by which or how many institutions can be a vital datapoint to better understand how or which program and software was chosen to digitize collections. The data of how many collections choose which program or software can also be a datapoint in the forward motion of creating a standardization, as common methods can be a simpler and more streamlined datapoint of why they were chosen, and how to better incorporate those elements into the best field-wide practice protocols. This is the aim of this question- to better understand and pinpoint similarities of not only programs and software, but also to establish if there are any underlying reasons as to why those were chosen, or similarities, benefits or challenges of digitization that those programs or software solved.

The fifth survey question, "What programs or software is your museum using to catalog, store and manage the digital collection?" was chosen to include in the survey due to the similarities as in question four. Just as important as digitization, the catalog and storage of a digital collection is vital for the overall success of transferring the specimens to a digital format. Without the catalog and storage aspect, digitization in and of itself is severely less advantageous for a collections department. The wording of separately emphasizing catalog and storage is intentional. A catalog is an amalgamation of contextual information that is bonded to the specimen that has its own program and software. A storage and manager system can be a separate program and software to maintain the needs of maintaining longevity with digitized specimens. The aim of this question is similar to the fourth as well- to understand, identify, and

compare similarities, benefits or challenges of the digital catalog and storage systems in different vertebrate paleontology collections.

The survey's sixth question, "Do you keep copies of digital specimen data in duplicate and/or in additional forms of storage? Is there a back-up storage plan in case of technology malfunctions?" is asked to establish whether or not collection departments backup their digital data and if they prepare for any technological issues. This is broken into two sub questions to clarify that having copies of digital specimens is considered a separate necessity in collection departments, as well as if collection managers both have and know their protocols should technological issues occur. The aim of this question is to gather data on if copies of digital data are kept, if so, how, and in what form. The second part is to establish not only if institutions have a back-up storage plan, but what it is and how they implement it if necessary.

The seventh survey question, "What security measures does your museum have in place to protect digitized collections from unauthorized access and data breaches?" is included as to assess the vitality of the security involved for collection departments to maintain the digital knowledge of their archives. Data breaches and unauthorized access are phrases of specific understanding that encompass risk of the safety of the archives, thus both are included in the question. Institutions must have protocols and practices in place to protect their digital data- just like physical locks, protocols, and practices that are incorporated for their physical archives. The aim of this question is to establish the current practices of security in collection departments, and if there are any specific challenges or similar issues in the department. This is to assist in discovering overlapping gaps in security that must be solved during an establishing of standardized best practices.

The survey's eighth question, "How does your museum address copyright and legal compliance in relation to their digital collection?" was chosen for the survey due to the complicated aspect of copyright and the lack of established legal guidelines for digital specimens in museums. It is important to establish how museums are currently navigating these issues in order to explore possible solutions. Copyright and legal compliance are both asked specifically in the same question to highlight how they are overall connected, yet must be separately handled by the collection manager, especially in the digital aspect. The aim of this question is to establish how individual museums are not only implicating the current lack of clarity, but to connect similar understanding and implications of both copyright practices and legal compliance protocols. This is an area that requires a lot of coordination to help an institution establish standardized best practices.

The ninth survey question, "In your opinion, are/were there any challenges specific to your institution that you have/had to consider while digitizing?" is a focus on the collection manager's experience with their specific department in terms of challenges and how they either overcame them, or how they are currently attempting to overcome them. This was worded to focus on the challenges that can be individually experienced, but could be useful data for an overall picture of the realistic struggles that collection managers go through to successfully digitize their specimens. This data could establish a starting point for a collaborative base of how to establish best practices on a field-wide level, as it deals with the current struggles that are happening as digitization is being implemented. That is the aim of this question- to find a potential similarity in challenges that could establish a starting point of standardization in hindrance solution.

The survey's tenth question, "Are or were there any specific challenges that your museum overcame when digitizing its collection?" is a follow up to the ninth survey question, and one that is focused on how collection managers overcame the challenges that their specific department overcame. The reason this is a separate question than the ninth is to separate the challenges from the solutions and focus on the methods that collection managers took to overcome them. Similar challenges that are mentioned in survey question number nine can have different solutions, and this is reflected in the aim of this question. If collection managers face similar challenges but have different solutions, then it can be an additional resource of data for archival staff to have access to when deciding how to overcome the various challenges of digitizing their collections.

The eleventh survey question, "How does your museum handle change in technological advances with regard to your digital collections?" is another key question to understanding the core challenges to adding a standardization of digitization in collections departments. Changes in technological advances can impact not only the ability for a museum to participate in digitization but also hinder long-term storage efforts. Not being able to upkeep usable data can lead to an institution not digitizing their collections at all, thus creating a gap in the global commonwealth knowledge. The aim in asking this question is to increase the understanding of how individual museums operate in terms of technological challenges will be a large factor in creating a long-term sustainability in their digital data catalog.

The survey's twelfth question, "What is your museum's process for loaning out digital specimens?" was included to assess how digital specimens are loaned out and compare them to the process of physically loaning out specimens. Physical loans are an established and common practice in vertebrate paleontology laboratories, however, digital loans are still in the process of

being a solidified practice of collection departments. This question is asked in such a way to clarify and separate the digital loans from their established physical loaning process. The goal of this question is to compare various institutions with each other to find a possible commonality in how the digital loan process can be implemented in a sustainable and standardized practice, given the current copyright, legal, and ethical protocols.

The thirteenth question in the survey, "Does your museum participate in open-access data?" is asked to determine if the institution is fulfilling their accessibility roles, both for research and for the public. The generalization of the question is to help determine the overall level of accessibility that the museum already participates in. Given the information that will be gleaned from the other questions relating to digitization and resources, asking about accessibility will create data on how each institution displays the results of their digitization efforts-regardless of where their digitization process is at. The aim of this question is to compare institution open-access levels with their digitization levels, then compare that data with other institutions for a similarities and differences marker of how resource and digitization levels affect open-accessibility, if at all.

The survey's fourteenth question, "What is your protocol for sharing digital data with researchers?" is included, as digitization has one of the largest impacts on the research sharing aspect of institutions. The data from the open-access data will support this question as well, as researchers require accessibility that is enhanced a great deal through the digital efforts of institutions. Comparing the protocols between institutions will enhance a system of sustainable accessibility between institutions and the researchers that benefit from digitization. The phrasing of sharing digital data was emphasized, as in the twelfth question, due to the long-established protocols of loaning out physical specimens, and to emphasize how different the process is for

loaning out digital specimens. The aim of this question is to look for similarities and differences that can highlight a path for establishing best practices for digitally sharing data amongst researchers on a field-wide level.

The fifteenth question of this survey, "What is your protocol for sharing digital data with the general public?" is similar to the fourteenth, as institutions have an ethical and moral obligation for their data to be available to the public. As with researchers, the public benefits from the information of the digital datasets, if more on an educational level. This question is asked separately from researchers to specifically highlight the differences in how institutions interact with requests for research collaboration and how institutions present open-access to and for the general public. The phrase sharing digital data is similar to question fourteen to mirror the legal and copyright elements of sharing digital data in a safe manner, and how institutions balance it with open-accessibility. The aim of this question is to once again look for similarities, differences and any points that stand out to create a more standardized form of open-access for the general public specifically.

The sixteenth inquiry on the survey was to ask the respondents to, "please briefly describe your best practices for managing and maintaining any digital specimen archives under your care. (Amount of storage space, number of volunteers involved with the digital collection, percentage of collections that have been digitized, etc.)." This was asked of the respondents to assess where their current best practices and protocols currently stand. The aim of this question is to gather a general overview of how their current operations are being run, what the staffing or volunteer situation is like, as well as any other types of information they find relevant to the study given the questions they have previously answered. This question was worded in such a way as to leave it more open-ended to allow for aspects of best practices that the individual

institution deemed relevant or important enough to list would not only be incorporated in comparison, but to also determine if there were aspects of best practices that this thesis does not cover but should be studied further.

The seventeenth and final question of this survey was, “Is there any other information that you would like to share with us, or to have mentioned or noted in the study?” This type of question is also important in a survey, as it is an open-ended question that allows for the survey respondent to include what they feel is important, just as in the sixteenth question. The aim of asking a generalized question like this is to gather any remaining thoughts, opinions, or miscellaneous topics that are related to but not directly asked by the survey. If similar or different ideals are included in this portion of the survey, it will be important to compare and include in the thesis for inclusion of best practices, or possibly a direction into future studies of collection management protocols.

3.2 Sampling

Overall, there were five participants that responded to the survey. Each institution was given a consent form and survey questions, which they could supplement with additional information such as loan request paperwork at their discretion. The analysis process was to receive the surveys, read and critically consider them, and interpret them given the topics and themes discovered in the research portion of the thesis. The ethical considerations of this paper pertain to the persons who filled out the responses of the survey. Respondents were given the option to remain anonymous, as well as ensured that their participation is completely voluntary. This was done to maintain ethical and moral adherence to the rules laid out by the University of Oklahoma.

The study participants were sought out due to their connection with museums or institutions, their relevance of specific collections of relevance to this study, as well as their likely knowledge of the intricacies related to adding digitization to the collections under their management. The participants had informed consent (see Addendum I), and confirmed they were over the age of 18 and could legally participate and be included in this study. Volunteers, administrators or other areas of museum staff were not able to participate, as they were considered unlikely to have an intricate knowledge of current digitization practices. Thus, collection managers were invited to fill out the survey given their knowledge of their collections, equipment, and staffing information.. Participants were emailed the consent forms and survey sheet, with an invitation to include any other information they thought would be beneficial. This was done in consideration of time and work duties of the participants, as well as fulfilling the action research methodology, by outlining details of their current best practices in digitization, as well as establishing where challenges or improvements could be lingering within their systems.

3.3 Data Analysis

The data from the survey was analyzed and grouped to best approach themed topics of how museums access their needs in digitization. The survey responses were collected and grouped by individual questions to better access specific information of each museum respondent. After establishing the theme groups, a comparison of the answers were compiled to group similar and different needs that each museum considered during the digitization process and their current practices. Those groups were then compiled into a set of themed work for the discussion portion of this thesis.

This was done to highlight the full realistic practices, benefits, challenges, concerns and successful results that the museums are currently experiencing to better highlight the overall

picture of the survey responses. Additionally, the results were read over for information such as the amount of times a topic was mentioned, any numbered data, or aspects of digitization that were not directly asked of the respondents. The respondents were listed by institution then compiled together by question to better highlight the similarities, differences, and comparative goals of this thesis.

Four main themes were grouped together for the discussion portion of this thesis: Resources and Funding; Staffing and Collections Transitions; Standardization, Technology, and Tool Utilization; and the final theme, Digital Storage and Long-term Sustainability. With the results organized in such a way, the full context of the current research, structure of the survey, results of the survey, and the organization of those results were combined into a collective set of next steps in the conclusions chapter of this thesis.

Chapter 4: Results

The following chapter is a summarization by the author of the survey respondent's answers. The museums and institutions that replied to the survey are anonymous, but their full responses are included. The survey was comprised of seventeen questions, which are overviewed in numerical order in the following section for both clarity and structural purposes. Overarching themes and observations of responses are synthesized in Chapter 5: Discussion. The surveys were sent out to eleven museums and/or university-level institutions across the United States of America. Of those who received the survey, five of the surveys responded- 3 museums, and 2 university-level institutions. While these responses are less than half of those that were sent out, I was pleased with the response rate and received a broadly useful amount of data.

In addition to the response of the survey, some museums and institutions included additional supplemental paperwork from their collections and otherwise expanded on their

opinions in regard to and opinions on best practices. These have been incorporated into the following results. Some of the surveys required the collections managers to reach out to additional staff members or did not know information related to certain questions. This type of response reflected how individual collections are often heavily intertwined with other areas of their institution, and how this can create unique challenges within departments when they need to collaborate with other areas in their goal to digitize specimens.

What follows are the survey questions used in this study with comment on response quantity and content:

1. To the best of your knowledge, what proportion of your museum/ institution's funding comes from public versus private sources? Is your institution considered a public or private institution?

The funding structure or source for respondent museums varied widely, which was a goal of the study. Two museums surveyed identify as predominantly privately funded, while one is fully publicly funded. One museum is a public institution, with funding consisting of 50% public funds and 50% private endowments. One museum declined to respond.

2. How many specimens are in the collection that you are responsible for? How many are available on a digital repository?

Specimen cataloging is a core responsibility of museums and varies widely based on individual needs. One museum reports having 106,000 cataloged fossils, in addition to many uncatalogued specimens. Another museum notes it houses 22,876 specimens, of which 122 are represented by 439 individual media files. Over 10,000 fossils from one responding museum are available through the online repository Morphosource (2024), although this number does not reflect the full catalog, as those available online are representative of their digitized specimens.

Additionally, one museum reports about 2 million fossil objects, with 300 available as 3D scans on MorphoSource (2024). Lastly, one museum notes around 115,000 cataloged specimens, with many more in its care that are uncatalogued.

3. How does having a digitized collection connect to the museum's mission and vision statements? In what forms were the specimens digitized? (scanning, photos etc.)?

One museum reported that they prioritize an electronic catalog, and reported housing 12 terabytes of 3D data alongside 50,000 2D photographs. Another institution reported that its specimens were digitized using laser scanning or CT scanning at off-site locations. In one instance the institution has micro-CT scanned data of specimens that are then constructed for use as projection data. The museum did not elaborate on the meaning of the projection data usage. One museum discusses its efforts with 3D CT scans but acknowledges funding issues in recent years. Another respondent stated that digitization is a strong priority for its mission and vision statements, even if not explicitly stated in their charter. The respondent noted that digitization is a major focus of their collection center, which has a digital media specialist on site. Photos and CT data constitute the primary forms of data in their lab.

4. What programs or software do/did your museum use to transition specimens to digital archives?

Programs and software can vary greatly between museums. One museum has used the program 4D (2025) but is in the process of switching to the database program EMu (2024). Another museum reported utilizing a mix of Meshlab (2025), Meshmixer (2025), Artec Studio (2025), ScanStudio (2025), RapidWorks (2025), Dragonfly (2025), and Aviso (2025) in their efforts to find a suitable digitization program. One museum noted that VG Studios (2025) is heavily used, along with AVIZO and DICOM readers. Nonetheless, they do not have an

established program for archiving yet. Another museum reported that they use several systems but mainly rely on EMu (2024), which they chose because it can record catalog data and support multimedia records simultaneously. One museum did not provide a response.

5. What programs or software is your museum using to catalog, store and manage the digital collection?

Two museums mentioned their transition from 4D to EMu (2024), as it is a museum-wide collection management system that incorporates features from their previous NetX system (2025). Another indicated that they use the MorphoSource (2024) data site. A third respondent reports that they also use EMu (2024). One museum noted that they have images stored on hard drives in their CT lab, as many bulk-storage solutions lack sufficient financial or physical support for long-term viability. They raised concerns about "dead storage," understood to be when a Principal Investigator's (PI) funding ends or the PI moves on, resulting in a loss of digitization support within the institution. As a result, there is no funding to transfer this type of data should the need arise. Currently, they rely on MorphoSource (2024) for longer-term storage; however, knowledgeable and retainable staff are rare for maintaining the backlogged hard drives.

6. Do you keep copies of digital specimen data in duplicate and/or in additional forms of storage? Is there a back-up storage plan in case of technology malfunctions?

One museum reported that their 4D (2025) system is backed up onto two separate external hard drives, while their EMu (2024) system is backed up onto external servers. They identified that the Technology Department at their museum oversees the long-term preservation of collection data and assets. Another museum mentioned that they also back up their storage on hard drives. One institution focuses on functioning as a scanning facility noted that they retain backup data for two years; ownership and usage rights of the data are retained by the client.

Another museum stated that scans are funded through research grants or external researchers, and the data is secured by the museum institution until publication, which can create delays in scanning, storage, and available data. MorphoSource (2024) helps them in this by keeping scans private until publication. Another museum noted that while they have backups on external hard drives, their new system also stores data on their network.The respondent remained unclear about the protocols for handling malfunctions or IT issues, as there is no clarity on how such situations would be addressed at that institution.

7. What security measures does your museum have in place to protect digitized collections from unauthorized access and data breaches?

One museum reported that they have a separate server infrastructure from their master environment, with the individual collections team responsible for data accessibility. Another museum noted that their IT department handles these issues, although the respondent felt that specifics on this process are lacking. One museum did not respond, while two museums indicated that hard drives are not connected to their network. They noted that in their opinion this method enhances overall data protection. However, one institution mentioned that data from drives can be corrupted and that technology formats can change, potentially making their data obsolete or non-transferable. Given this, they rely on MorphoSource (2024) for continuing storage. Caveats to this include the need for continuous funding, as well as demanding effort from what they identify as their overtaxed and underpaid collections staff for maintenance.

8. How does your museum address copyright and legal compliance in relation to their digital collection?

One museum stated that they publish using various standardized forms developed by their institution. Another, a federal institution, operates under Public Domain and has no copyright

restrictions. However, they note that non-commercial use is permitted, and their capabilities within MorphoSource (2024) to restrict downloads. Another institution requires clients to sign a form before any scanning occurs, though many institutions rely on copyright statements created and utilized by MorphoSource (2024). One museum reported that they are currently revisiting these issues with their university's copyright and contract lawyers. Additionally, one museum stated that they have legal counsel to address such issues, but they are unsure of the specific protocols involved. At this institution there are Media Agreement Forms for researchers to sign, but generally these museums do not mandate that level of legal compliance for photographs, as it would require additional personnel to track forms and monitor how researchers use the specimens.

9. In your opinion, are/were there any challenges specific to your institution that you have/had to consider while digitizing?

One institution replied that they are instructed not to use sites such as MorphoSource (2024) or Sketchfab (2025); however, they are not provided guidance on having an internal alternative or database system to support digital data. Consequently, they use MorphoSource (2024) for publication services out of necessity for the time being. Another museum noted that moving terabytes of data is extremely challenging. Each request to access data must be treated separately, as the data cannot be regarded as a single entity. Data must be organized by department and sent individually, straining resources and staff there. Another institution highlighted that their CT lab was designed to function as an independent entity from their umbrella institution. Having been founded as a CT facility in the mid-1990s, they often found that contracting and copyright efforts were copyrightable, with rights granted to those building the models. Through researchers and licensing data, the media became the property of the

researcher through this transfer. However, as a result, they rarely received datasets for their own collections. Currently, this institution is fighting for raw scans of non-copyrighted work while legacy datasets are being updated to MorphoSource (2024). Securing funding for this effort has been challenging. Another museum reported that the biggest challenges with digitization remain time and money. As a team of two, they stated that there are not enough resources to meet the goals set by museum management. Data storage is another ongoing issue due to funding. One museum mentioned that there was nothing specific to their institution.

10. Are or were there any specific challenges that your museum overcame when digitizing its collection?

One museum stated that they rely on partner organizations to purchase scanners, and that computers designed and built for running gaming programs are often required to run the software and graphics necessary for CT data, but purchasing systems could not obtain the best options for working with scanned fossil material. Another institution reported that there are no clear answers for how to handle legacy digital data, nor industry wide standardization for rescuing corrupted files or drives. Currently, there is no automation for migrating data stacks from obsolete formats that the museum can easily utilize. Additionally, there is typically a loss of data or imagery when converting data from .RAW to .TIFF, .JPEG, or other formats. They noted that computational emulators from the gaming community could become an option in the future due to an interest in preserving outdated gaming systems, and they hope this interest will eventually translate to different digital formats. This issue remains one of the largest, most unavoidable, and vital to resolve. Lastly, one museum stated there was nothing specific to their institution, and one did not provide a response.

11. How does your museum handle change in technological advances with regard to your digital collections?

One museum stated that they have an IT team knowledgeable about the evolving community data standards, archival practices, and emerging platforms. This team decides whether to implement those changes into the museum's broader practices. Another institution reported that they often simply lose data and attempt to learn from it, making efforts to minimize data loss during future technological evolutions. For example, they maintain overlapping fallback strategies locally through digital and physical drives that are regularly copied from previous data set points. Additionally, the institution keeps database reports on physical cards, estimating that this method works better for queries than databases or quick references. Another institution notes that their IT department is responsible for this issue, although efforts have been made to increase overall data storage across their institution. The respondent noted that budgeting issues and technological advances remain core challenges for this institution. They utilize their machines for as long as possible and apply for grants to purchase new equipment, such as scanning electron microscopes, or partner with institutions that already possess the necessary equipment. One institution mentioned that this issue does not apply to their collections, while another did not respond.

12. What is your museum's process for loaning out digital specimens?

One museum noted that for the majority of their collections, digital assets are considered surrogates of the physical specimens and are thus not "loaned" out. Another institution stated that they process loans through MorphoSource (2024) or email correspondence, requiring non-commercial use agreements with the goal to ensure that the lienee will not share the data with others or host it on another site. Another museum treats digital specimens like any other type of

collection, involving a request, approval, and transfer. They then upload the data to MorphoSource (2024) and store it on both a local hard drive and a virtual drive. However, they note that some researchers do not respect the legal or ethical issues surrounding digital assets and share them freely among themselves or with others without the institution's knowledge or consent. This leads to instances where versions of digital assets end up sold by private companies or used in research or exhibits without proper attribution. Another museum reported that 3D datasets are loaned out in the same manner as physical specimens, with loan agreements addressing usage, credit lines, and time limits. For digital images, they send photos to researchers without additional paperwork, stating that it would be nearly impossible to track the usage of those images. Another museum did not respond.

13. Does your museum participate in open-access data?

All museums affirmed their participation in open-access data, with one museum stating that they adhere as closely as possible to FAIR (Findability, Accessibility, Interoperability, and Reuse) (see: Introduction) principles for datasets and other digital assets. They noted that digital media is made public at the discretion of the collection's teams, rather than other departments, and may be embargoed or redacted for ethical, cultural, and/or research reasons. Two museums added that some data is available on MorphoSource (2024) and credit this as their open access source, while one of those two further stated that they have not fully explored other open-access resources beyond MorphoSource (2024).

14. What is your protocol for sharing digital data with researchers?

One museum noted that research data is available to anyone via their Integrated Publishing Toolkit (IPT 2025), which aggregates data in an automated fashion. The data for the

IPT comes from their museum-wide collections management system, EMu (2024). Another museum referenced MorphoSource (2024) or email correspondence, as they require non-commercial use agreements and stipulate that the lienee will not further share the data with others or host it on another site. Another museum reported that they share raw scan data unless they own the 3D models. They use MorphoSource (2024) to manage datasets, which are available upon request. One museum did not provide a response.

15. What is your protocol for sharing digital data with the general public?

One museum mentioned that anyone can download data from their IPT and highlighted that they have a dedicated collections search site powered by their EMu (2024) system. Two museums stated that data sharing is generally done through MorphoSource (2024), and one museum elaborated that they also allow for email correspondence, requiring signed non-commercial agreements that confirm the lienee will not share the data with others or host it on another site. Another museum reported that the general public can request access to data through MorphoSource (2024). Yet another institution stated that they are a public collection and as such believe that images of their collection should be publicly accessible. They mentioned that their 3D models are creative works and are only shared after publication or with the permission of the researchers who generated them.

16. Please briefly describe your best practices for managing and maintaining any digital specimen archives under your care. (Amount of storage space, number of volunteers involved with the digital collection, percentage of collections that have been digitized, etc.)

One museum indicated that their best practice is to support networked systems that are centrally maintained within their institution. They noted that EMu (2024), NetX (2025), and DatoCMS (2025) are the primary systems used for their collections data and assets, and they are

considered critical museum software. The museum holds multiple licenses for this software, allowing use on various computers. Additionally, there is a licensed machine with an attached portable printer for the lab. Every few months, the museum retrieves and consolidates all records, updating them to the master license of the collections manager before distributing this copy to the other licenses. They also maintain additional external hard drives for backups and implement systemic auto-backups approximately every hour.

This institution also reports maintaining a set of four external hard drives for digital images. They have an estimated 45,000 2D images planned for uploading into EMu (2024), stored across two external hard drives: one with a capacity of 4TB and the other 1TB. They also have a growing amount of CT-scan data stored on a 6TB external hard drive (noted to be at capacity) and a 12TB hard drive (noted as half full). All of these data sets needed to be uploaded into EMu (2024). Regarding staffing, there are two main volunteers, one of whom comes in about three to four times a week. Further, they mention that all cataloged vertebrate specimens are represented in the program 4D (2025). As cataloging is research-driven, new cataloging occurs when research is conducted on the collection that leads to publication. They acknowledge having backlogs of uncatalogued and unprepared materials; however, they lack the staffing necessary to process these items until involved in a research project.

Management of their loans is handled with another standalone database, Double Helix (2025), which is an icon-driven relational database designed for Macs. This management is performed using a dedicated Mac equipped with its own backup external hard drive. The loan database is currently being migrated to EMu (2024). Another museum reports that their suggested best practice is to utilize a third-party online digital storage system such as MorphoSource (2024), supplemented by secondary and tertiary storage options that include on-

site storage tied to separate funding streams. The structure of these data should mirror each other in case of technological or security failure. They recommend always maintaining the original scans and photographic sets (for photogrammetry models), as well as other types of models wherever feasible. Additionally, they suggest that digital initiatives should be funded and staffed separately from physical museum collections and should be undertaken by staff dedicated to digital efforts. It is an unfortunate common occurrence that museum collection staff face time strains due to the dual responsibilities of digital projects and the management of physical collections. While they assert there should be a collections manager/curator overseeing the digitization staff, they emphasize that the digitization efforts should be distinct from the collection staff's duties.

They note that they have witnessed agencies funding digital initiatives at the expense of collections, with those funds being redirected to support collections and curatorial staff. As grants wind down, digital assets remain, shifting the burden of maintenance and management onto curatorial and collections staff. This practice effectively creates a new collection type for museums to manage, expecting staff to develop skills, secure funding, and incorporate new infrastructure to support it. They express concern that, in their experience, upper management is often unaware of the extensive effort, time, and resources the digital aspect of collections entails, as well as the benefits it provides to the institution. They further note that MorphoSource (2024) currently offers their best solution for managing and maintaining data. Nonetheless, they have unfortunately found that virtual storage is only as reliable as the funding source. Unlike physical collections, which can persist in the absence of funding, digital collections risk disappearing once funding concludes. If MorphoSource (2024) were to disappear, for example, they would need to back up the digital collection, and to do so, they would need to retrieve that data onto a

parallel storage site for backup, develop a new protocol for access, and likely face the loss of significant data related to the use of the digital collection.

Another museum respondent reported that they are still in the early stages of establishing best practices. Currently, they store all of the CT data on four or five multiple-terabyte external hard drives, with plans to eventually import the data into EMu (2024). More than half of their current loan requests pertain to CT scanning, leading to a constant increase in their digital collections. None of their current volunteers possess the necessary technological knowledge, but they plan to have technology-driven interns work with the data in the future to assist with its migration into EMu (2024). One museum stated that such practices are not currently in place at their institution, while another did not provide a response.

17. Is there any other information that you would like to share with us, or to have mentioned or noted in the study?

One museum remarked on the general lack of cohesion and standards in the microCT landscape. They suggest that institutions educate themselves about NoCTURN (2024), a grant-funded program that actively works to build and assist with the establishment of best practices regarding non-clinical research, including CT scanning, data storage and management, and data reusability. One of NoCTURN's (2024) goals is to enact what they call FAIR principles—Findability, Accessibility, Interoperability, and Reuse. Among NoCTURN's (2024) noted techniques is a "good, better, best" recommendation for CT data storage to be used by museums and other institutions. Additionally, they observed that even well-funded museums struggle with the digital aspect of their collections, while smaller institutions are often reluctant to integrate digital practices due to a lack of long-term storage solutions.

Another institution reports that they hold millions of objects, but they cannot estimate

how many have been scanned because they do not have direct access to most of the scans. They have 300 datasets on MorphoSource (2024) but limited access and control over legacy datasets. Moreover, they have no reliable method for locating them without the assistance of otherwise encumbered staff, who have other more pressing obligations related to grant funded projects. They noted that there is a lack of staff, funding, infrastructure, and established methods for supporting volunteers who could retrieve legacy data. Even if legacy data could be retrieved, it is uncertain what percentage would be worth salvaging, noting that it may be more time- and cost-effective to simply rescan. Recently, they have mitigated this issue by ensuring that all scans move directly to MorphoSource (2024) as soon as they are completed. However, this approach leaves the institution with a backlog of data, raising the question of whether it is worth the effort to manage and migrate this bulk of datasets.

They also note that they have previously undergone the process of digitizing educational resources for online use. With the support of grants, they digitized an estimated 500,000 specimens, which were organized on servers to ensure easy access for the public. This effort facilitated the creation of an online exhibit in collaboration with local schools at the time. However, the respondent cannot locate those efforts, and the current whereabouts of the educational resources are unknown.

With this context in mind, the institution expresses the opinion that these efforts have produced vast amounts of digital material for education, outreach, virtual exhibitions, and public sector use. However, they observe that the drive for digitization often diverts attention from collection building, collection care, and the core mission of museums. In their response they suggest a better model: funding educational groups that employ educators and digital content creators to produce digital resources. This could involve creators assisting the collections staff in

exchange for their time and attributing their results to the institution for access to the collections. Instead, they note that collection staff are losing time due to digitization grants at the expense of genuine collections care, leading to a loss of collection building and research.

They conclude by reporting that since 2011, they have been actively incorporating several collections made by other research associates into their institution's repository. These collections were previously compiled by professors at other universities who have either passed away or retired and the respondent institution is subsequently transferring these data sets to their museum's collections. Over the last 15 years, at least ten large collections of vertebrate fossils have been added to their repository in this manner. Additionally, they cannot identify a comparable large archive of field-collected specimens anticipated to be accessioned in the next generation. However, they can think of equivalents in digital datasets but question their viability when those researchers retire. Three institutions did not respond.

Chapter 5: Discussion

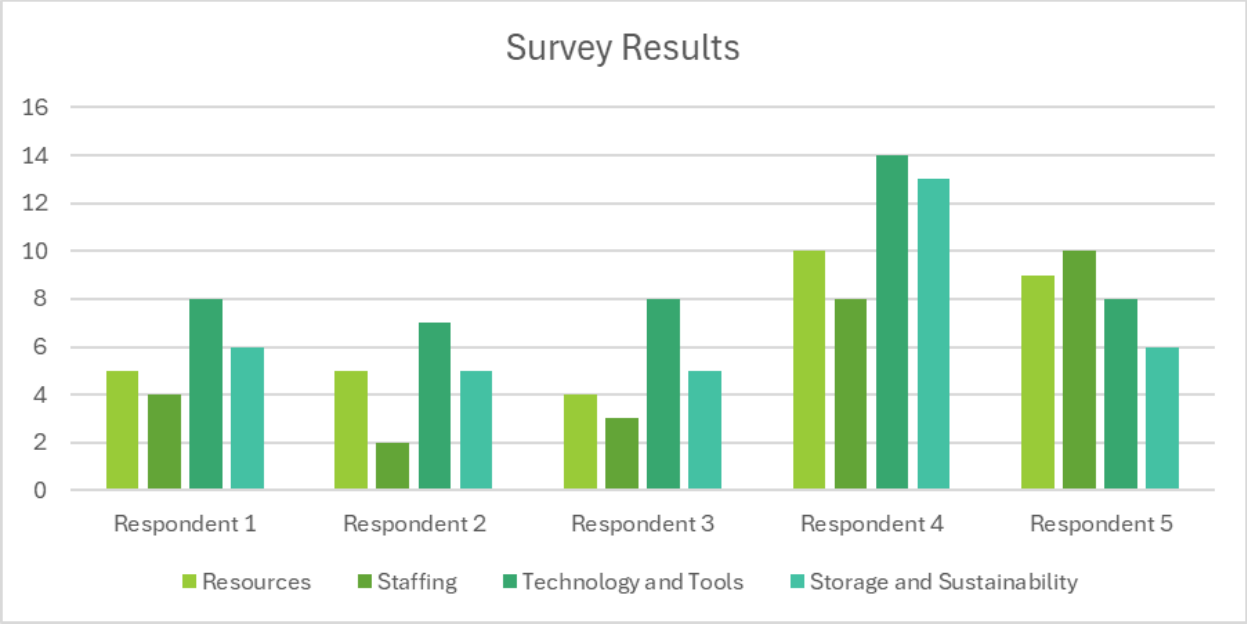

Figure 3. Response per Institution Graph.

The respondents of the survey noted numerous challenges and current best practices regarding the availability of digitization in vertebrate paleontology collection departments (see Figure 3). Overall, I identified four key themes from the results, which are discussed below. Issues regarding resources such as funding, staff issues, and technological barriers were all mentioned as key frustrations by the respondents. Additionally, security and long-term storage management were noted as challenges with no clearly identified solutions, and the implications of these challenges are discussed in Chapter 6.

5.1 Resources and Funding

The survey results showed that funding is a major factor in how museums determine their best practices for digitizing their specimens in collections. I found that this topic is the most consistently identified resource in the returned surveys mentioned either directly or indirectly by five out of five respondents. Whether the institution is funded privately, publicly or through grants, the allocation of those funds ultimately determines the feasibility of production for the collections department. The survey respondents noted different sources of revenue in the first question, such as being either privately or publicly funded with grant support, yet their issues were stated to be the same: a lack of sustainable funding for specimens to be digitized or to keep the large amount of digital storage in a safe and reliable format, as noted Question 9.

The second and third questions in the survey regard how many specimens are in the collection and how many are available digitally. The respondents reported not only how many cataloged and digitized fossils they have in their care but also acknowledged the large discrepancy in those numbers, and that they have many more uncatalogued specimens in their collections. While this may seem unrelated to a lack of resources on the surface, the institutions

directly noted a lack of funding, as well as a lack of available machinery or direction in solutions for these issues in Questions 9 and 10. Similarly, while there is assistance in other departments such as security or technology in Questions 11 and 16, there is a noted lack of cohesive plans of action in case of a breach, bug update, or sustainability plan in place in the respective respondents' institutions. These aspects of resources are just as important as funding and require a similar amount of planning, consideration, and execution.

5.2 Staffing and Collection Transitions

Museums that are awarded grants must still have adequate curatorial staff, even if they are only temporarily hired to create digital images of backlogged datasets. The main issue mentioned by the respondents in Questions 5, 7, 16, and 17 was that the needs of physical collection care clash with the time allowed to digitize specimens for different grants. One practice is for volunteers and amateur paleontologists to assist employed staff under the supervision of the institution; however, expanding this to a national or international level would require a detailed discussion with many participants in the field to clarify ethical and moral guidelines to avoid looting or damage to sites (Haung et al. 2020). Museums are generally understaffed at both the full- and part-time levels in the field and in the lab, making this a systemic issue.

Some of the museums respondents in Questions 7 and 16 that their collections staff is not numerous enough to support digital efforts. Two museums reported that designated "Technology Department" is responsible for the long-term preservation of data and other digital assets in Questions 6, 9, and 11. Additionally, the security staff is tasked with protecting the collection from breaches, and the lawyers on staff are responsible for ensuring that the loaning process for digital media complies with national U.S. standards in Questions 12 and 17.

This creates a complex network of information that can be lost or misrepresented unintentionally by the various parties. These parties assist with standards, archiving practices, and emerging platforms within the museum, but they are still vulnerable to being hacked or malfunctioning. A significant vulnerability is also how the legal and copyright compliance are handled by the Legal Department or through MorphoSource (2024), which are not specifically known by the staff mentioned in Questions 8, 9, and 12. Additionally, another museum notes in question twelve that it is more difficult to track photos than other forms of digital media, resulting in a gap between creating the data, sharing the data, and ensuring the data remains only with those who have approved access.

Another challenging aspect includes staff for whom when digital responsibilities are added, they become overworked and proportionately underpaid in regard to their other duties, as mentioned in Questions 7, 16, and 17. Thus, adding many digital tasks is sometimes too much in both time and effort considerations, causing the digital projects to fall to the background until there is a specific request to digitize certain specimens. A repeated issue among respondents, particularly in the Questions 9 and 16, attributes this large gap between institutions to the hours of effort it takes to upload data onto their respective databases. When this occurs, there can be a strain to configure or retrain staff to digitize, instead of having an established protocol and system that the staff is already implementing. One museum in Question 16 noted this as well- that there is a sizable difference between the work that needs to be done and the staff, time available, and funding required to do an appropriate and responsible job alongside their current responsibilities.

The issue of staff retention, mentioned in questions sixteen and seventeen, has also been a known issue in museums since their establishment in the modern world. Museums have

expanded the growing and ever-changing responsibilities of curation upon staff who already have many duties regarding research, education, curation, and preservation of their collections. To fully add digitization, which encompasses a myriad of information, duties, and evolving knowledge to stay relevant towards, it is difficult for curators, staff, and volunteers to manage and maintain all of their responsibilities in a timely and comprehensive fashion.

Another reoccurring issue regards retention and turnover of both staff and volunteers. Museum staff have volunteers organize the collection in a certain way, but when volunteers or staff members move on, a new staffer- with new ideas on how best to manage the collection- may instigate a reorganization of the collection to fit the new system. This concept is mentioned in Question 17 of the survey. A lack of staff is a vital element of digitization, as even with the proper technology, fully funded support, and plans for digital media integration, without properly trained and devoted staff, the digitization is often not completed; the effects of this are noted in Questions 2, 7, 16, and 17. These concepts connect to the study as the respondents all mentioned how they struggle with staffing issues and find it difficult to navigate digitization without staffing support from the museum.

Another aspect that is not exclusively unique to paleontology, but assuredly applies to vertebrate paleontology, is that of collection transferal. Collection transferal, mentioned in question seventeen, is when a principal investigator passes on or retires, and their collections or repository then needs to move to the institution to which the fossils belong. These collections can be a form of borrowed fossils that need to be returned or fossils that are collected and studied by a principal investigator who works in a separate laboratory from the museum under whose name the fossils were gathered.

Grants are often awarded to individual paleontologists who go out in the field to collect vertebrate specimens relevant to their specific research. These specimens take up physical space and must be preserved for present and future generations to study. The preservation is done either in a lab, museum, or school, depending on where the paleontologist is employed. However, when the scientist retires or passes away, their collection is then shifted to their affiliated institution or one that is unrelated to the paleontologist's place of employment, depending on the circumstances. Shifting these specimens has a vital component: the context and data connected to the specimens must also be transferred along with the physical collection. This can be a difficult aspect of paleontology to uphold, as it can be complicated depending on the circumstances of who is transferring the specimens, how it is organized, and where the specimens are being transferred to.

Digitized specimens operate in much the same fashion. The transfer of digital data can be a complicated and delicate process. Various passwords and programs must be known in order for the digital specimens to be accessible and manipulatable across platforms. Currently, there is no reliable way to transfer physical specimens consistently, much less in a digital fashion, due to the added confusion of how digital datasets are collected, what state of organization they are in, and the many passwords or locations of equipment where they are kept. This connects to the study as the respondents mention how this element of paleontology translates not only to the physical specimens and the context that comes with them, but also to digital data and the protocols involved that must also be transferred and accessible to others in the institution.

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reliable way to transfer physical specimens consistently, much less in a digital fashion, due to the added confusion of how digital datasets are collected, what state of organization they are in, and the many passwords or locations of equipment where they are kept. This connects to the study as the respondents mention how this element of paleontology translates not only to the physical specimens and the context that comes with them, but also to digital data and the protocols involved that must also be transferred and accessible to others in the institution.

Different types of media can create difficult transfer of, or even harmful loss of data, corruption of the media, or a loss of the images completed during the transfer process. This is a core challenge of digitization that must be resolved in a best practices model to enable open-access sourcing in museums and between researchers. One respondent mentioned in Question 10 how emulators could possibly assist with the transfer of data types. However, this technology is still being tested in the gaming industry and is not yet developed enough for the field of museology. Legal, ethical, and technological standards play into the different forms of digital media that must be transitioned in order for paleontological work to thrive. This connects to the study, as the respondents mention how there is a gap in how data is transitioned that puts the context and data at risk of being lost or compromised. Given how context is the core of all paleontology, this issue is a critical point that must be resolved in digitization practices moving forward.

5.3 Standardization, Technology, and Tool Utilization

The response to the survey highlighted the lack of collection standardization within many institutions. The respondents all have various circumstances and solutions for their digital collections, including using a combination of multiple departments, programs, and resources to assist in their digital media goals, as discussed in Questions 6, 7, 8, and 10. This is helpful, as

multi-field and multidisciplinary integration will assist institutions in reaching an efficient, adaptable, and accessible solution to the growing digitization issue (Yan and Xin 2022). Building technology that has cohesion and standards of operation is a challenging task and requires cooperation across various stakeholders. In addition, organizations such as NoCTURN (2024) and iDigBio (2024) create sub-groups of various coordinating collaborators and were mentioned in Question 17 (Gignac et al., 2024).

However, standards and cohesion in digital spaces are rare, difficult to define, and can be multifaceted in their design. Many different fields, including institutional Tech Support, Graphic Designers, Code Writers, Paleontologists, and Museum Staff, to name a few, are required to work together to ensure that a digital collection is accessible and transferable between the different and necessary parties. Another issue mentioned by the respondents is how digital data is treated as supplemental data, as discussed in Questions 12, 14, 15, 16, and 17; however, digital identities are as much primary data as the physical specimens in regards to information and preservational needs. This connects to the study as the respondents mention a general lack of standardization within the field, that digital data is not as supported by the administrations in the museums, and that there is a weak understanding of how vital digitization has become over the last few decades. This general misunderstanding must be addressed for best practices to be implemented in the field.

However, standards and cohesion in digital spaces are rare and difficult to define, and can be complex with so many facets assisting in its design. Many different fields, from Tech Support, Graphic Designers, Code Writers, Paleontologists, Museum Staff and more are required to work together to ensure that a digital collection is accessible and transferable between different and necessary parties of researchers, museum staff and the general public. Another issue mentioned

by the respondents is how digital data is treated as supplemental data in Questions 12, 14, 15, 16 and 17, however, it is as much primary data as the physical specimens regarding information and preservation needs. This connects to the study as the respondents mention how there is a general lack of standardization within the field, that digital data is not as supported by the administrations in the museums, and as such, there is not an understanding of how vital digitization has become over the last few decades. This misunderstanding must be addressed for best practices to be implemented in the field.

In connection with the lack of standardization, some of the respondents in Questions 5, 7, and 10 also mention how their current types of data sets are difficult to convert to other software and how, in some circumstances, irreplaceable data is lost without the opportunity for rescanning, costing further resources to be expended. Additionally, these data sets routinely contain thousands of bytes of data, which puts into perspective how much effort goes into scanning and preserving the information. It can be time-consuming to move files, as well as presenting a risk of data corruption due to a failure during transfer. Currently, there is no method of restoring corrupted data, which is another issue when transferring files, for example, from .raw to .tiff to .jpeg. One institution in question sixteen, meanwhile, has its current best practices noted as using MorphoSource (2024) while having a secondary and tertiary data storage system in-house that is separately yet reliably funded in case of security breach, server issues, or network crash. They note the importance of their internal storage system mirroring the one they have online as well as their backups, to effectively spot and retrieve data in the event of corruption or other issues.

Vertebrate paleontology collection practices are enhanced through digitization. Many museums with various artifacts and non-vertebrate paleontological specimens benefit from

digitally preserving specimens, and those benefits pertain to vertebrate specimens as well. These benefits include being able to see a full and accurate representation of the specimen, as 2D or audio descriptions can create a distorted perception of the specimen. 3D digitization creates a more nuanced, manipulable, and focused copy of the specimen that is comparable to or even improved upon molding and casting. 3D copies of specimens are a digital equivalent to molding and casting, offering more detail and easier transferability. In addition to these benefits, vertebrate specimens are rarer and more fragile than non-vertebrate specimens due to how they are preserved, thus highlighting the need for preservation (NPS 2024). While non-vertebrate specimens and other artifacts can also benefit from this thesis, vertebrate specimens emphasize the urgency and importance of preserving rare and delicate fossils and their context.

Technology is an ever-changing challenge for museums, despite the goal that a sharable format continuously enables a museum to maintain public trust and relevance—both with their general audience and with fellow researchers. Evolving technology creates a substantial barrier for museums in terms of standardizing how digitization is handled in their collections departments. For example, in Question 2, the largest collection among the respondents has about 2 million specimens in their physical collection, yet only 300 are available digitally. Comparatively, in the same question, another institution has over 100,000 specimens on MorphoSource (2024) that are available and open to the public, with many more specimens in their collections that are uncatalogued and not translated into digital media. All museum respondents noted this disproportionate amount of physical to digital specimens, and their numbers differed wildly. Other noted issues included the technology evolution protocols, staff, and funding available to each institution, as well as handling the circumstances of both their collections department and the museum management support system in Questions 5, 7, 9, and 17.

Additionally, the respondents mentioned how many programs they attempted to use in order to establish long-term technology solutions in Questions 5 through 7. Some of the respondents mentioned using 4D or Double Helix, while others used a combination of Meshlab, Dragonfly, and Aviso in questions 4 and 16. However, funding and a lack of standardization in the field create a misconnection of resources and anti-interoperability between museums and researchers. Especially as the funding for some scanning is grant work, one respondent reported that there can be a lag between scanning and storing the data so it's readily accessible. Another institution notes that its best practices are the software EMu (2024), NetX (2025), and DatoCMS (2025) for the collections data in Questions 5 and 16, and these are considered critical to maintaining museum collection operations. Yet, they acknowledge that it is not a permanent solution, as updates and different software can be difficult to manage. This trickles into various issues, such as loans.

Digital specimens are sometimes loaned out in much the same way physical specimens are for some respondents, through an appeals process, while also using MorphoSource (2024) for ease of transfer, legal, and ethical issues. However, online systems can also experience security breaches, as some assets can still be shared without authorization and end up sold to private companies. Given its draw-backs, MorphoSource (2024) is not an end-all; it is merely the newest in a lengthy effort to attempt standardization in the field for most of the respondents. Yet it could also be used to establish how a standardized system could be unifying across the field of museology.

Using associated technology software and hardware is mentioned by the respondents as being time-consuming and complex. Researchers must navigate through temporary solutions, with many different programs having been attempted in the past to create a sense of

sustainability. They note the frustration of long-term storage in Questions 5, 6, and 17, and there is an overall usage of respondents who currently use MorphoSource (2024) and EMu (2024) as a means of accessibility, loans, and the legal realities of publication and internal software. This connects to the study as the respondents establish that there is a large gap in sustainable technology in use across the board, and that reliable backup storage systems are not as feasible as they need them to be, expressing that there is no current form of correction for this solution.

Resources such as digital tools, physical equipment, and both software and hardware programs used by institutions are how digitization methods are established in the museum's collection department, as well as how the institution continues to establish its digitization efforts in perpetuity. One museum noted in question 9 that the digital media cannot simply be shared by the museum as a whole, as it must be separated and sent to different departments and curatorial staff. The respondents noted they have hired more staff to compensate for issues associated with this but also note that it is a temporary fix for a much larger issue. Another institution in Questions 6 and 11, maintains accessibility with backup redundancy, from Specify to the Cloud, to Access and physical card catalogs that hold information. Ultimately, technology advances so fast that funding, programs, and staffing needed to upkeep the information can be lost when there is a transition or update of the formats used, and thus the need for so many fail-safe methods of accessibility. However, this can be complicated, and there is a large risk of error with lost media, a lack of updating all the backups, and a loss of data from human error.

The museums respondents mentioned in Questions 2 and 3 that they have electronic catalogs of their collections; however, it is a mix of photos, CT scans, laser scans, and 3D scans. These collections and the plans to upload them are accessible through legal and ethical means, as often referenced in the institution's mission statements, if indirectly. This is due to the fact that

the digital versions of the specimens are still considered a part of the collections department, and as such, they should be available to patrons and researchers alike to fulfill those statements and ethical duties. Morphosource (2024) is frequently mentioned as being kept for legal and storage efforts between creating the scan and publishing the data, as well as a boilerplate legal placement for work that is not yet finished between the various departments and the researchers who need access to the data.

Internally, most of the respondents discussed using EMu (2024) for collection management and Morphosource (2024) for external collection management. Reasons for this included that certain software, like the previously used 4D for one respondent in questions 4 and 5, does not support online usage, and thus they are making the switch to EMu (2024), which has that component. An issue noted by one institution in question nine is that sites such as MorphoSource (2024) are not a preferred course of use for digital media; however, at present, there is no other alternative offered, so they use it out of necessity for their publication needs. However, it should be noted that both repositories, MorphoSource (2024) and EMu (2024), are remarked to be merely the current solution to a more long-term issue and not the whole solution in and of itself.

All survey respondents are participating in open-access data according to Question 13, some through MorphoSource (2024) and others through their internal collections team. Additionally, this is a practice with which they share digital data with researchers: MorphoSource (2024), internal paperwork, or EMu (2024) protocols. In Question 15, it is established that the general public can access digital specimens through EMu (2024), MorphoSource (2024), and legal agreements from the institution's internal legal protocols to fulfill their open-access goals.

The various tools, including scanners, software such as EMu (2024), and equipment such as cameras, are all vital laboratory resources for paleontologists to not only use but also to be familiar with in order utilize their full potential for digitization. This connects to the study as the respondents mention their frustrations with backup technology and frequently shifting organizational programs, while having a desire to establish sustainable open access with patrons and researchers. However, they feel there are many challenges that are stalling that goal from becoming realized.

Regarding tool utilization, all of the respondents mentioned using outsourced support such as MorphoSource (2024) for their current best practices, while one specifically mentioned additional resources such as NoCTURN (2024) and iDigBio (2024) in Question 17. Organizations such as NoCTURN (2024) create multi-layered communities to cultivate easier management, maintenance, and knowledge of the different technologies to produce digitized material (Gignac et al. 2024). While volunteer or amateur paleontologists may assist with these matters, resources still need to be vetted by the paleontologist in charge before moving forward (Haung et al. 2020), which is why collaboration with such programs can benefit staff in museums. Technology is constantly upgrading, which creates a strain on museums as funding is not as constant as the updated software or hardware.

Museums must legally, ethically, and technologically be up to date in order to maintain integrity, relevance, stewardship, and public trust. Therefore, despite the difficulties in staffing, finances, and coordination, institutions must ensure they are placing their resources properly to meet their ever-growing list of duties and responsibilities. Organizations such as NoCTURN (2024) or iDigBio (2024) can assist with that balance. Institutions mention struggling not only to

obtain staff but also with sustaining other means of assistance, such as volunteers, amateur enthusiasts, or upper management support.

Outsourced online repositories such as MorphoSource (2024) are also increasing the researchers' legal and ethical obligation regarding sharing files only with the consent of the loaner. Knowledge and navigation of these types of resources and behavior guidance are key elements of NoCTURN (2024) and iDigBio (2024), who plan on increasing the outreach aspects and further promoting education for programs (Gignac et al. 2024). Online repositories and organizations such as MorphoSource (2024), EMu (2024), iDigBio (2024), and NoCTURN (2024) are all making a concerted and collaborative effort to acknowledge the various staggering issues between museums and the completion and accurate usage of their digital collections, which have been noted by the survey respondents across multiple questions in the survey. While these efforts are ongoing, they are continuously evolving and making the effort to progress despite the challenges that digitizing a vertebrate paleontology collection provides.

This connects to the study as the respondents mention how they enlist repositories such as EMu (2024) and MorphoSource (2024) for solutions to their current digitization issue; however, it remains an impermanent solution, as funding and long-term sustainability are not solidified with these programs. Further, the respondents in Questions 5, 7, 16, and 17 mention how staff do not know the technology of digitization well enough, and there is a large learning curve with the process of digitizing specimens that has to be repeated whenever there are new volunteers, staff, or students. iDigBio (2024) and NoCTURN (2024) are part of other advantages to aid in digitization; however, institutions still must create an internal code of standardization on a field-wide basis that the museum staff is familiar and comfortable with. Organizations such as NoCTURN (2024) and iDigBio (2024) can lend assistance with some of the challenges of

digitization, such as programs or establishing a community of knowledgeable resources for staff to reference. However, each museum must have a reliable and standardized course of action to maintain their digital specimen duties.

5.4 Digital Storage and Long-term Sustainability

Storage is another issue that nearly all the respondents mentioned as an important challenge to their digital media goals. One institution in question seventeen notes how NoCTURN (2024) and iDigBio (2024), among others, are making a designated effort in producing long-term solutions for primary metadata that focuses on accessibility and dissemination of changing technology (Gignac et al., 2024), in the context of how these solutions can be an asset to museums. Digitizing a vertebrate paleontology collection is time-consuming, expensive, tedious, and requires a diversity of museum resources to both create and maintain. However, the most important aspect of creating a digital repository is the long-term preservation of the specimens. Nonetheless, it is often argued that the benefits of connection and relationship building to museum audiences through digitization projects make the sacrifices worth the efforts involved.

Many of the respondents in Questions 5, 6, 9, 11, 16 and 17 also mentioned how the storage of digital specimens is complex, especially given the relationship between the often massive computational size of these repositories and subsequent secure long-term storage. The museum's resources may not be large enough to support the digital collection long term, as official programs can be a financial burden that grants cannot support long-term given their funding framework. This is one of the most important aspects of digitizing a vertebrate paleontology collection and consistently remains the most difficult issue to address for institutions. This connects to the study as the respondents mention how long-term storage is a

common issue with no true resolution in place. Technology, tools, staff, and funding are all very malleable in the museum field, thus creating a complex and difficult path to standardized digitization. One of the institutions noted in Questions 9, 10, and 17 that data plans that included 12TB of 3D data, which is a sizable amount that did not even include redundant legacy datasets. That is no small amount of both digital media and staff efforts by the museum and requires a lot of resources and funds to reach without a reliable method of sustainability.

A lack of reliable funds and carried into perpetuity creates a lack of effort or drive complete the massive amount of work behind digitizing collections and brings their future completely into question. This is reflected in respondents in Questions 3, 5, and 9, 16 and 17, when they remarked how funding expired on their first 3D scan system and that this is a recurring issue. It creates a lack of incentive for museums to digitize their collections if they do not know whether the vast amounts of storage data will be supported in the years to come. Museums must house their digital storage in a safe and reliable format, as well as secure the longevity of those storage methods. Many respondents mentioned in Questions 5, 8, and 9 that they either already have or are planning to move the storage to an off-site server, such as MorphoSource (2024), while also having backup storage for security reasons on external hard drives- protecting them from being breached over the internet. However, this has its own issues due to hazards such as fire, damage to the hard drive, and corrupted files. How museums currently operate does not support the longevity of the digital information of their specimens.

This issue of digitization is extremely complex; however, digital collections can open new horizons for research as well as optimize outreach for the institution, and thus it must be viewed as a viable funding resource by museum management. Museums must have funding for equipment, staffing requirements, data conversion, and both short-form and long-form storage

for their digital archives. This system of equipment, conversion, and storage, unfortunately, requires funding for the license, equipment, and storage of metadata. While funding such as grants can be a useful start for museums, a more long-term solution is needed for digital archiving to be established and sustainable in perpetuity. This connects to the study as the respondents all mention how vital funding is, yet how unsustainable it can be. Finding solutions to this issue is a core component of properly and safely incorporating digitization into the collections' practices.

One institution mentioned in question nine that their CT Lab was set up to be self-funding from the start, which could help with establishing a self-funding digitization element of standardization for museums. For example, researchers or private citizens could pay for the results and copyright or license. However, this still requires an evaluation of results, as the institution did not receive data during this time and is now pushing for copies of the RAW files, creating another legal challenge to navigate. Ultimately, digital media is work that currently centers on the backlogging of the majority of collections, which require a large amount of attention, effort, funding, and knowledgeable staff.

This is challenging, as museums struggle with those elements in many of their departments already. The museums that responded to the survey discussed in Questions 2, 7, and 17 together noted that specimens that were either digitized or had plans to be digitized had been slowed or halted due to a lack of funding, as well as the pressure of current or more profitable projects being prioritized by museum management. This exacerbates the issues of digitization for collection managers, who noted feeling discouraged in this situation. This type of discouragement was mentioned by one respondent in Question 17 who noted how collaborative their 500,000 specimen resources are for civilian education yet unable to find that information

currently. There was a likely lack of sustainable support for education, and thus that effort and time are no longer being used as a benefit; consequently, the time and effort involved feel wasted.

Museums must reevaluate the actions they are currently taking for long-term storage; however, this is difficult given the lack of reliable technology or tools currently available for massive computational storage options, nor the management support to seek solutions. This connects to the study as the respondents mention different hazards, an overwhelming backlog of specimens that they also lack the storage to keep, and a lack of support, which discourages them from participating in digitization. These are core issues that must be addressed for a standardized digitization system and for best practices to be implemented on a field-wide basis.

Chapter 6: Conclusion

6.1 Limitations and Challenges of Study

The biggest limitation to this study is how few respondents there are to this survey. There also needs to be a reformatting of the questions posed to create a more encompassing viewpoint of the state of collections, which are outlined in the "Gaps of Knowledge" section in Chapter 6 of this study. Another limitation is how many varieties of software and hardware options there are, as well as a lack of depth on how a standardized practice can be built that encompasses overarching vertebrate paleontology archival needs. The amount of both software and hardware options creates a systemic compilation, as there is a large amount of diversity that inhibits standardization. Many of the museums are using EMu (2024) or MorphoSource (2024) at the time in this survey, however, that can change rapidly with technological advances. Other issues can arise as well, such as buggy updates, budget changes, or a breach of security data.

The main challenges of this survey were deciding what questions to ask. The questions needed to establish a baseline of how the museum is run and how many specimens were in the collections, but also needed to explore the digital means of preservation, what their methods are and challenges to completing the goals they have set in place. This was a complicated decision, as digitizing specimens requires a lot of moving parts to be successful, but the survey could not be too long or it would be too arduous to answer. The questions were chosen based upon the best efforts of the author, but there is still a lot of research and surveys to be done in this area.

This thesis had five different institutions respond to the survey, with various statements for how they manage their current best practices. These replies were compared for similarities and differences. While many of these institutions as well as others are operating in good faith and the best they are able to with their circumstances, many of them face the same issues of low and unsustainable funding, a lack of guaranteed safety in long-term storage, and a lack of museum resources within their department. However, it must be noted that the survey respondents are very large museums and institutions. This can skew the evidence that was gathered, as large museums and institutions have different resources and amount of collections than smaller vertebrate paleontology collections. Further and more detailed research into smaller museums and their best practices would be necessary before field-wide implications of digitization are established.

6.2 Knowledge Gaps and Future Research Directions

This study conducted a survey of seventeen questions aimed at ascertaining how museums currently build, grow, and maintain their digital collections. The questions were chosen to establish a baseline understanding of how the museum is funded, how many physical specimens are currently in the collection as an estimate, and how many specimens have already

been transferred to digital material at the time of the survey. The responses were a mix of information but overall indicated issues of finances, staffing concerns, space, and long-term storage.

From the survey responses, all of the institutions noted a substantial numerical difference between their physical specimen archives and their digitally cataloged specimens. While it was an estimate, more direct numbers in later surveys would need to be collected across a wider range of institutions to fully understand how many specimens are being digitized. However, from this survey, less than one percent of their collections are digitally preserved, which emphasizes how little of their physical specimens are digitized, given how important this goal is for museums.

Further research would also be needed to determine how their digitizing format is decided upon and how the digitization is funded in extreme detail. Most of the respondents use MorphoSource (2024) for their formatting and storage, but researching how they each came into contact with and made the decision to move forward with funding is an important element for future studies on how museums make complex and long-lasting decisions regarding their digitized collections. Additionally, asking for the format in which they are saved, both online and in the museum, would be beneficial when studying how to safely transfer different formats such as .jif, .tif, .stl, etc., as well as how often they share their digital data. Also, a study on the percentage of corrupted files and drives would be useful in establishing how museums choose to protect their storage online and on-site, in what formats for short-term and long-term storage, and which formats are is not ideal or safe to use.

Additionally, complications in digitizing specimens would need to be studied in depth regarding how there is an intertwining of the various departments in an institution. Many of the

respondents rely on other sections of the museum, such as technology and security, to solve potential issues or breaches. While a museum does rely on various departments to work efficiently, the loss of data or unauthorized use of the collections department is a serious issue and must have communicated protocols in case of digital emergencies. The technology department, with an excellent supplemental support for the collections department, should be a separate and dedicated aspect solely for the collections staff.

Different departments and sharing protocols would require staff that is fully funded and established in their roles. Many of the respondents mentioned how funding is a major source of issues in their departments. While it is common in museums, there could be a financial link between how the institutions are funded and how many specimens they can afford to digitize and store, both long-term and short-term, as well as how that connects with their specimen, institutional, financial, and long-format storage needs. Further and more in-depth statistics would need to be collected to study how the financial and staffing aspects, two of the most discussed topics of the survey, would need to be supported for the museum to expand its digital collection and storage of specimens. A deep dive into how funding is obtained and handled in museums would be a core aspect of creating a systemic digitizing operation within the museum that has protocols, processes, and knowledgeable staff and volunteers who work together efficiently.

Museums create one of the most unique and valuable experiences for their patrons: the education and preservation of humanity's commonwealth for the benefit of present and future research (Bakker et al., 2020). The information housed in museums is irreplaceable data, which incorporates various responsibilities, including stewardship, public trust, and ethics to build and adhere to. Museums have a "social value" that has continued to rise throughout recent decades and has a larger interest on a global scale than ever before in history (Crew 2017). However, to

maintain that relevancy, museums must constantly adopt and adapt to the changes of their audiences, which have expanded from their local communities, to the interconnected global stage. This means that museums have had to be mindful of political, legal, and societal changes in the past few decades more than in the past (Lindqvist 2012; Woodward 2012).

Paleontology, specifically, has also had to maintain the skill of adaptation within the field. Adhering to context being the most vital element of the science, the means through which to not only obtain but manage large amounts of contextual data has become a core responsibility paleontology (Vollmar Macklin and Ford 2010). The quality of data has been enhanced from time- and resource-consuming efforts such as manual data collection or drawing specimens by hand to GIS tracking precise location information, CT scanning photography, and 3D mesh preservation of otherwise destructive ecology samples (Vollmar Macklin and Ford 2010; Nelson and Ellis 2018; Sutton et al. 2016). These technological efforts have created and enhanced the entire paleontology field through the acceptance and adaptation of the tools and collaboration now available to us in the modern age.

The museums that responded to the survey discussed their parameters for digitizing their collections and the challenges they face in determining the best practices for their individual needs as institutions. This is one of the most difficult aspects of creating new and unstandardized responsibilities in a field that has a constant need to grow and evolve to remain relevant to the public yet uphold the public trust and stewardship of preserving the past. The museums that responded to the survey were thoughtful, thorough, and encompassed their experiences of best practices according to their abilities.

Museums being responsive to the shift in needs is a skill that many collection managers must cultivate. Institutions must have a “meaning-making” mindset when it comes to designing

exhibits, educating their audience, and collaborating with fellow researchers while also being responsive to feedback and changing protocols in their field (Simmons 2015). They must balance this with their other responsibilities such as organization, preservation, and maintaining ethical standards of stewardship.

One example of adaptation in recent years is the increased use of digitization and GIS-based data gathering. Digitization allows for greater accessibility through online technological advances, while GIS allows for a more accurate gathering of context with which to supplement that accessibility. Digitization also allows for a faster and more accurate transfer of information from the primary source, such as a physical or digital scan of a fossil, to the database of an institution (Silva Mano et al. 2024; Reed et al. 2015; Vollmar, Macklin,and Ford 2010; Kjærgaard 2012; Smith 2010). However, these practices are still not reliable or sustainable enough to become a widely usable best practice across the field, as demonstrated by the response to the survey, which is why a blend of older practices and modern technology is often used.

Museums in the past few decades have had to adapt to a lot more change than in previous centuries. The initial infrastructure of displaying and educating about past objects has morphed into a societal necessity for cultivating an environment of science, interpretation, application, and establishment of preservation for the future. Natural history museums have taken on many responsibilities, duties, and codes of behavior due to these changes. With this history in mind, it is time for natural history museums to be open to yet another critical growing obligation: the incorporation of digitalization into their daily practices, codes of ethics, and their legal and preservation duties (Bakker et al. 2020; Winkler 2004; Medina et al. 2020; Krishtalka and Humprey 2000).

Creating reliable workflows and stable forms of funding while also building properly supported staff are key topics for the survey respondents. To bring these common issues into a solution in the modern age, digitization will need to be a larger priority than is currently accepted. This will benefit not only the education of the patrons but also the collaboration with many different sciences, including large grant-focused areas such as ecology and conservation that can, in turn, benefit the museum's network and net worth (Karim et al. 2016; Nelson and Ellis 2018). The purpose of this thesis is to understand how current museums establish what best practices their vertebrate paleontology collections are currently using, evaluate those practices against the current literature, and add to the evidence of how institutions can best re-evaluate their current abilities by incorporating digitization into those practices.

6.3 Best Practices in Short- and Long-term

The biggest factor that the survey results showed was the need for establishing clear duties for the digital aspect of collections management. The current protocols are arbitrary, require multiple departments, and do not have a firm foothold in either staff or funding availability. One possible short-term solution that museums will likely take advantage of to gain the breathing room for accessing the long-term success of a digital best practices protocol is to obtain volunteers or public participation from amateur scientists who are skilled and knowledgeable about the constant rotation of technology. This will help to increase the knowledge of the collections department without causing strain on the currently available resources.

Additionally, a volunteer role as a delineation specialist for public interactions and digital media can be obtained until more permanent solutions can be implemented. These roles would serve as a registrar between the public and the collections manager to handle the digital data,

follow up with public or researcher inquiries, manage digital media requests, and delegate information between said parties. This would alleviate the pressure on museum and collections staff, allowing them to focus on their current resources while enhancing and expanding the digital aspect of their collections. This would also be a temporary system of procedures while the museum addresses a more long-term standardization of their best practices. Assistance from NoCTURN (2024) or iDigBio (2024) can be an additional temporary or long-term resource for museums that are struggling in this aspect.

There is another issue of addressing constant technological advances, the expense of current digital aspects of collections, and an overwhelming amount of duties placed within the collections department without matching support from the institution. Another solution that museums will likely adopt is to obtain a volunteer position specifically for digital media and three-dimensional printing aspects of the museum, collaborating with a digitalization professional or another museum with a similar or larger repository. Short-term grants can be used as a means of boosting relevancy, networking, or solidifying their research base until longer and more sustainable grants can be obtained. These types of solutions will need to be adaptable to obtaining other revenue sources for long-term solutions, as having multiple revenue sources can create a certain level of stability. Museums could find this a challenging issue; however, creative solutions are often a part of collections management when funding is not reliable.

My thesis adds to the evidence that natural history museum collection managers are not equipped or supported either by stable finances or staff, and feel overworked or overwhelmed with responsibilities. However, despite this, they state that they are managing their collections to the best of their abilities. To increase support, institutions can focus more of their resources, or on obtaining more resources, to bolster their collection management needs. With collaboration

and a change in business focus, curatorial practices can create a stronger connection with relevancy in a way that benefits the museum as a whole (Colella et al. 2020; Winkler 2004).

One of the largest long-term challenges a museum faces when determining best digital practices is the budgetary realities of operation, while the other the constant evolution of technology. These issues, along with the growing responsibilities of museums, are not being met with an increase in budgetary or staff assistance, and this is a core aspect that must change for long-term stability. One solution museums could consider is eventually creating a digital department that would be able to obtain specific grants and shareholder support to help implement an established set of best practices for the digitization of their collections.

Long-term and systemic solutions for determining best practices addressing the challenges museums face include adding more support that is intertwined with how the museum operates as a whole. Moving forward with digitization as a priority, it would not be surprising if the systemic best practice for a museum in terms of digital protocols is to eventually create a separate and specialized department that combines parts of the education, technology support, security, collections management, and administration departments into an individually financed digital department. While this would require a combined effort from staff in the museology field to create, a collaborative effort would establish a sustainable budgetary framework, prolonged establishment, and hybridization of duties that would fulfill the stewardship and public trust of the museum.

Throughout the results of this thesis, there is an indicated need for a change in how museums operate. For a permanent, long-term solution to the issues mentioned in the survey responses, institutions should invest in facilities that specialize in digital practices to alleviate some of the resource strain in the long-run. In that scenario, the facilities can generate

knowledgeable employees who can hone specialized knowledge and skills in a timely manner and increase the number of specialized standards while lessening the strain on the museum staff, who may need to retrain volunteers, manage budgetary issues, or deal with a lack of digital space (Gignac et al. 2024).

A digital curator would work closely with multiple departments to create a network of knowledge and responsibilities that currently get deprioritized by collections staff due to other, more urgent duties. Furthermore, a specialized department would be able to understand the technical aspects of data transferring and storage on a local surface, while potentially having the time and resources to deepen connections with associates such as NoCTURN (2024) and iDigBio (2024) to manage backlog specimens and enhance open access and engagement with online collections. Additionally, they would be able to become experts in MorphoSource (2024) and EMu (2024), as well as other digital repository programs, to lessen or prevent the loss of data or funding related to such assets of the museum.

Museum collections staff have their own vast array of issues, focuses, and responsibilities to manage. With a digital curator additionally on staff, it could be a way to funnel certain focuses to support not only the staff and physical specimens but also create a manageable and funded subdivision of the museum itself that would not take away from the overburdened stewardship of the institution. Museums can bridge the financial gap of optimizing data with their collections by also increasing their stakeholders into a broader range of individuals. This would include knowledgeable interested parties in the technicalities and intricacies of creating a digital space for their collection through proper channels that are constantly changing. While digital projects are currently considered project-based, allocating the funding in combination with knowledgeable staff and the considerable backlog of specimens that all the respondents

mentioned there would provide a justifiable amount of workload to sustain a constant and dedicated digital staff member (Card et al. 2021; Vollmar, Macklin, and Ford 2010).

My thesis evidence adds to the growing amount of accessible literature on how museums will need to continue to adapt to modern focuses, as they have been for the past few decades. The main issue is the same across all survey respondents: the lack of available funding and staffing, as well as the complications of technology. These issues are extremely complex, and museums should create a separate allocation of resources for digitizing specimens and archiving those specimens. Providing staff and funding to enhance storage infrastructure will cultivate a collection that has a vital balance of physical and digital data for the institution to utilize to their full benefit. Technology is continuously becoming less costly and more advanced, and museums will likely have no other option but to prioritize being more aware of the growing benefits to their collection departments. This is especially true in the aspect of globalization and maintaining an ethical and legal reputation in the modern age. Institutions will need to continuously adapt to international and interdisciplinary resources to sustain relevancy and public trust (Colella et al. 2020; Campana et al. 2015; Kaiser et al. 2023).

6.4 Thesis Implications

This thesis study was performed with the intent to ascertain what the current practices are in institutions with regard to their vertebrate paleontology collections department, as well as discussing their challenges and the benefits of digitizing their archives. Through a survey process, institutions state that they are experiencing low amounts of digitization support from their respective management. They lack the dedicated staff, sustainable funds, and a plan in place for long-term storage repositories. Additionally, there is little guidance for the best methods of long-term storage, security, and protocols for technological transitions or errors.

The survey also highlighted the benefits of digitization. The results of this study add to the literature regarding how vital digitization is becoming with regard to primary data and how globalization is increasing through technology to enhance relevancy and research collaboration. The institutions noted multiple layers of enhanced relevancy by adding digitization to their standards of practice via research collaboration, community engagement, and open access. Overall, these practices increase an institution's accessibility, collaboration, and preservation of the context and images of the specimens.

With the growing necessity for a digital collection due to factors such as globalization, open-access elements, and technological advances, museums must once again adapt to cultural and societal changes. This means that they must adopt new protocols and practices in order to best provide education, entertainment, and fulfill their public duties to their audiences and researchers. By making a concentrated effort to expand their resources to establish a digital collection best practices system, they will also ensure ongoing public trust and stewardship, increased interaction, enhanced relevance on a global scale, and create a more complete picture of the prehistoric era for researchers to study. My thesis adds to the evidence that, although digitization can no longer be a lesser priority for institutions-- it must become as necessary a practice as the preservation of a physical specimen-- there is a lot of standardization that must occur to fully implement digitization on a field-wide basis. Inevitably, this importance will need to be reflected by institutional support in financing, staffing, and constant adaptations to evolving technology.

The goals of this study were to understand how many specimens have been digitized, what tools institutions are using to digitize them, and what benefits and challenges the institutions face in the process. Ultimately, the survey respondents reported that very little of

their overall collection has been digitized. They are mostly using a mix of 2D and 3D digitization technology, such as photographs or CT scanning. They report a lack of administrative support while also experiencing an increase in collaboration with researchers and patrons alike. While these are some of the results that were discussed previously, they reflect the overall position of digitization in vertebrate paleontology collections-- digitization is increasing more rapidly in necessity than it is in practicality.

The next goal of the survey was to assess how respondents determine their best practices for standardizing the process of digitizing and storing their data for public access over both a short and long period of time. Other questions, such as how security and storage issues are handled and what solutions they are incorporating, if any, into their practices were also raised. The survey showed that the respondents are simply doing what they can give the state of the broader field-wide issues-- they are working within their individual parameters of support to expand into digitization, given the lack of resources and guidance. Security is currently outsourced rather than addressed through collaboration within their institutions, and storage is currently handled individually, given the lack of solutions from multiple angles regarding formatting choices, data loss, and long-term financing. My thesis qualitatively studied the current best practices of museums that are digitizing specimens in their vertebrate paleontology collections.

This was done to assess similarities and differences that can be used to increase field-wide protocols and guidance of daily practices. Through the efforts of the respondents, this thesis has produced evidence that adds to the field-wide literature on the considerable gap between how museums implement digitization and the fundamental necessity that digitization is becoming in the modern natural history museum. To fully adhere to and benefit from the ethical stewardship

inherent in vertebrate paleontology collections, institutions must allow for open access on a global scale and stabilize that ability over the long term. However, the challenges reflected in the survey appear to be shared on a field-wide basis as well-- a lack of administrative support, a lack of technological ability to constantly transfer data, and the issue of storage management. The overarching absence of standardization in the entire process of digitizing specimens compounds into a loss of context, collaboration, and irreplaceable specimen data. While there are several efforts at standardization such as NoCTURN (2024) or iDigBio (2024), there must be a stronger focus on solving the broader issues of standardization by individual museums rather than investing in temporary solutions to systemic problems.

Appendices

Appendix 1

Consent to Participate in Research
University of Oklahoma

You are invited to participate in a thesis research survey about your museum's digital collections information and management practices.

If you agree to participate, you will complete a 20-minute survey. You may experience these risks:

Collection of demographic or geographic location data that could lead to deductive re-identification: You will be asked to provide demographic information that describes you and your museum. We may also gather information about your geographic location in this research. Different combinations of personal and geographic information may make it possible for your identity to be guessed by someone who was given, or gained access, to our research records. To minimize the risk of deductive re-identification, we will not combine identifying variables nor analyze and report results for small groups of people with specific demographic characteristics. There are no benefits to participating in this research. Your participation is voluntary, and your responses will be anonymous. However, the name of your organization will be used.
We might share your de-identified data with other researchers or use it in future research without obtaining additional assent from you.

The de-identified research data, variables, demographics, etc., may be uploaded to an online data repository platform where it would be publicly available for anyone interested in using it.

Even if you choose to participate now, you may stop participating at any time and for any reason. If you have questions about this research, please contact:
Sage Cromwell, student PI, at sage.e.cromwell-1@ou.edu and/or Dr. Jacqueline Lungmus at jklungmus@ou.edu.

You can also contact the University of Oklahoma – Norman Campus Institutional Review Board at 405-325-8110 or irb@ou.edu with questions, concerns or complaints about your child's rights as a research participant, or if you don't want to talk to the researcher.

Please print this document for your records. By providing information to the researcher(s), I am agreeing to participate in this research.

Are you 18 years of age or older? No___Yes
No (If no- cannot participate) IRB # 16849
IRB Approval Date 02/08/2024

Appendix 2

Thesis Survey Questions:

To the best of your knowledge, what proportion of your museum institution's funding comes from public versus private sources? Is your institution considered a public or private institution?

How many specimens are in the collection that you are responsible for? How many are available on a digital repository?

How does having a digitized collection connect to the museum's mission and vision statements? In what forms were the specimens digitized? (scanning, photos etc)

What programs or software do/did your museum use to transition specimens to digital archives?

What programs or software is your museum using to catalog, store and manage the digital collection?

Do you keep copies of digital specimen data in duplicate and/or in additional forms of storage? Is there a back-up storage plan in case of technology malfunctions?

What security measures does your museum have in place to protect digitized collections from unauthorized access and data breaches?

How does your museum address copyright and legal compliance in relation to their digital collection?

In your opinion, are/were there any challenges specific to your institution that you have/had to consider while digitizing?

Are or were there any specific challenges that your museum overcame when digitizing its collection?

How does your museum handle change in technological advances with regard to your digital collections?

What is your museum's process for loaning out digital specimens?

Does your museum participate in open-access data?

What is your protocol for sharing digital data with researchers?

What is your protocol for sharing digital data with the general public?

Please briefly describe your best practices for managing and maintaining any digital specimen archives under your care. (Amount of storage space, number of volunteers involved with the digital collection, percentage of collections that have been digitized, etc.)

Is there any other information that you would like to share with us, or to have mentioned or noted in the study?

Bibliography

Adrain, Tiffany S., Budd, Ann F., and Adrain, Jonathan M. 2011. “Digitizing Collections: Experiences from the University of Iowa Paleontology Repository Digitization Project.” *The Geological Curator*. 9(5): 291 - 299.

Agosti, Donat, and Egloff, Willi. 2009. “Taxonomic information exchange and copyright: the Plazi approach.” *BMC Research Notes*. 2(53): 1-9. https://doi.org/10.1186/1756-0500-2-53)

Allam, Ahmad Zuhdi, and Yulianto, Kresno. 2019. "Museum Management: A Critical Point in Making Museums Relevant." In *Culture and International Law*. CRC Press.

American Alliance of Museums. 2024. “Ethics, Standards, and Professional Practices.” Effective May 26. https://www.aam-us.org/programs/ethics-standards-and-professional-practices/code-of-ethics-for-museums/.

American Museum of Natural History. 2024. “Collections Management.” Effective May 18. https://www.amnh.org/research/anthropology/collections/collections-management.

Artec Studio. 2025. “Artec Studio 19: Digital Twins from 3D Scans, Photos, & Videos.” Effective March 2025. https://www.artec3d.com/.

Aviso. 2025. “Aviso Platform.” Effective March 2025. https://www.aviso.com/platform.

Axiell. 2024. “EMu Documentation.” Effective May 20. https://emu.axiell.com/support/documentation/how-to-documents.

Baker, Robert J., Bradley, Lisa C., Garner, Heath J., et al. 2014. “‘Door to Drawer’ Costs of Curation, Installation, Documentation, Databasing, and Long-Term Care of Mammal Voucher Specimens in Natural History Collections.” *Occasional Papers, Museum of Texas Tech University.* 323: 1–15.

Bakker, Freek T., Antonelli, Alexandre, Clarke, Julia, et al. 2020. “The Global Museum: Natural History Collections and the Future of Evolutionary Science and Public Education.” *PeerJ.* 8:e8225. 1-40. http://doi.org/10.7717/peerj.8225

Blackburn, David C., Boyer, Doug M., Gray, Jaimi A., et al. 2024. “Increasing the Impact of Vertebrate Scientific Collections Through 3D Imaging: The openVertebrate (oVert) Thematic Collections Network.” *BioScience*. 74: 169-186. https://doi.org/10.1093/biosci/biad120.

Boessenecker, Robert W. 2022. “Amateur Collectors are Critical to the Study of Fossil Vertebrates: A Case Study from Two Neogene Localities in Northern California (Santa Margarita and Purisima Formations).” *Palaeontologia Electronica*. 25(1): 1-16. DOI: 10.26879/1199.

Boyer, Doug M., Gunnell, Gregg F., Kaufman, Seth, et al. 2017. “MorphoSource: Archiving and Sharing 3-D Digital Specimen Data.” *Paleontological Society*. 22: 157-181. DOI: 10.1017/scs.2017.13.

Bradley, Robert D., Bradley, Lisa C., Garner, Heath J. et al. 2014. “Assessing the Value of Natural History Collections and Addressing Issues Regarding Long-Term Growth and Care.” *BioScience*. 64(12): 1150-1158.

Broekhuijsen, Mendel, van den Hoven, Elise, and Markopoulos, Panos. 2017. “Design Directions for Media-Supported Collocated Remembering Practices.” *Proceedings of the Eleventh International Conference on Tangible, Embedded, and Embodied Interaction.* DOI:10.1145/3024969.3024996.

Brown, Kathryn. 2020. “When Museums Meet Markets.” *Journal of Visual Art Practice.* 19(3): 203-210. DOI: 10.1080/14702029.2020.1711488.

Brown, Karen, and Mairesse, François. 2018. “The Definition of the Museum Through Its Social Role.” *Curator: The Museum Journal*. 61(4): 525- 539.

Camarero, Carmen, Garrido M. José, and Vicente, Eva. 2011. “How Cultural Organizations’ Size and Funding Influence Innovation and Performance: The Case of Museums.” *J Cult Econ*. 35: 247-266. DOI: 10.1007/s10824-011-9144-4.

Campana, Stefano, Scopigno, Roberto, Carpentiero, Gabriella, et al. 2016. *Proceedings of the 43rd Annual Conference on Computer Applications and Quantitative Methods in Archaeology.* University of Siena 1240.

Card, Daren, Shapiro, Beth, Giribet, Gonzalo, et al. 2021. “Museum Genomics.” *Annual Reviews of Genetics*. 55: 633-659. https://doi.org/10.1146/annuriev-genet-071719-020506.

Carpinone, Elana C. 2010. “Museum Collections Management Systems: One Size Does Not Fit All.” Thesis diss. Seton Hall University Dissertations and Theses (ETD). 2366.

Choi, Seung, Park, Yong, and Moreno-Azanza, Miguel. 2024. “Protocol for Electron Backscatter Diffraction (EBSD) Analysis of Fossil Eggshells. Journal of Vertebrate Paleontology. E2363210. 1-12. DOI: 10.1080/02724634.2024.2363210.

Cieri, R.L., Turner, M. L., Carney, R. M., et al. 2021. “Virtual and Augmented Reality: New Tools for Visualizing, Analyzing, and Communicating Complex Morphology.” *Liverpool John Moores University*. DOI: 10.1002/jmor.21421.

Crew, Hayley L. 2017. “Social Value in Museums and Funding Priorities.” Thesis diss. University of Washington.

Colella, Jocelyn P., Stephens, Ryan B., and Campbell, Mariel L. “The Open-Specimen Movement.” *BioScience*. 71(4): 405-414. DIO: 10.1093/biosci/biaa146.

Copyright.gov. 2024. “Overview.” About Section. Effective December 2024. https://www.copyright.gov/about/.

Crockett, Cenetria Leshun. 2024. “Preserving Archaeology in the Digital Age: Evaluating Strategies for Effective Curation and Database Management.” Thesis Diss. Electronic Theses and Dissertations. Paper 4333. https://doi.org/10.18297/etd/4333.

Cunningham, John A. 2021. “The Use of Photogrammetric Fossil Models in Palaeontology Education.” *Evolution: Education and Outreach*. 14(1): 1-7. https://doi.org/10.1186/s12052-020-00140-w.

Cunningham, John A., Rahman, Imran A., Lautenschlager, Stephan, et al. 2014. “A Virtual World of Paleontology.” *CellPress.* 29(6): 347-357.

D’Andrea, Andrea, Conyers, Michale, Courtney, Kyle K., et. al. 2022. "Copyright and Legal Issues Surrounding 3D Data." In *3D Data Creation to Curation: Community Standards for 3D Data Preservation*, eds. Jennifer Moore, Adam Rountrey, and Hannah Scates Kettler. Chicago: Association of Research and College Libraries.

DatoCMS. 2025. “DatoCMS: Simply Put, The Most Complete, User-Friendly, and Performat Headless CMS.” Effective March 2025. https://www.datocms.com/.

Davies, Thomas G., Rahman, Imran A., Lautenschlager, et al. 2017. “Open Data and Digital Morphology.” *Royal Society Publishing*. 284(20170194): 1-10. http://dx.doi.org/10.1098/rspb.2017.0194.

Delfino, Davide, and Nizzo, Valentino. 2018. "Understanding and Accessibility of Pre- and Proto-Historical Research Issues: Sites, Museums and Communication Strategies." *Proceedings of the XVII UISPP World Congress.* 17(Session XXXV-1): 59-69.

Donaldson, Devan Ray, and Bell, Laura. 2019. "Security, Archivists, and Digital Collections." *Journal of Archival Organization*. 1-20. https://doi.org/10.1080/15332748.2019.1609311.

Double Helix. 2025. "Double-Helix Technology." Effective March 2025. https://double-helix.com/technology-strategy/.

Đukić, Marina, and Alebić, Luka. 2018. "Digital Collections Up Close: Research of Current Condition and Digital Museum Collections Optimization Attempt." *Reality in Media Arts, Media Language and Media Education*. 5(1):185-213.

Dragonfly. 2025. "Dragonfly About." Effective March 2025. https://dragonfly.comet.tech/.

Ellwood, Elizabeth R., Dunckel, Betty A., Flemons, Paul, et al. 2015. "Accelerating the Digitization of Biodiversity Research Specimens Through Online Public Participation." *BioScience Oxford Journals*. 65(4): 383-396.

Fan, Cheng-Wei and Wang, Yu-Hung. 2020. "The Concept Study of Knowledge Value Added in Museum Digital Archives." *WSEAS Transactions on Advances in Engineering Education*. 17(2224-3410): 99-106. DOI: 10.37394/232010.2020.17.13.

Fogarty, Robert S. 2016. "The Future of Museums: Challenges and Solutions." *The Antioch Review*. 74(2): 221-226.

Fouseki, Kalliopi, and Vacharopoulou, Kalliopi. 2013. "Digital Museum Collections and Social Media: Ethical Considerations of Ownership and Use." *Journal of Conservation and Museum Studies.* 11(1): 1-10. DOI: http://dx.doi. org/10.5334/jcms.1021209.

Geismar, Haidy, and Müller, Katja. 2022. "Postcolonial Digital Collections: Instruments, Mirrors, Agents." *The Routledge Companion to Media Anthropology.* 258- 271. doi:10.4324/9781003175605.

Gignac, Paul M., Aceves, Valeria, Baker, Stephanie, et al. 2024. "The Role of Networks to Overcome Large-scale Challenges in Tomography: The Non-Clinical Tomography Users Research Network." *Tomography of Materials and Structures.* 5: 1-22. https://doi.org/10.1016/j.tmater.2024.100031.

Gilmore, Charles W. 1941. “A History of the Division of Vertebrate Paleontology in the United States National Museum.” *Smithsonian Institutions U. S. National Museum*. 90(3109): 305-377.

Ginsburgh, Victor, and Mairesse, François. 1997. “Defining a Museum: Suggestions for an Alternative Approach.” *Museum Management and Curatorship*. 16(15-33): 1-19.

Haug, Carolin, Reumer, Jelle W. F., Haug, Joachim T. et al. 2020. “Comment on the Letter of the Society of Vertebrate Paleontology (SVP) Dated April 21, 2020 Regarding ‘Fossils from Conflict Zones and Reproducibility of Fossil-Based Scientific Data’: The Importance of Private Collections.” *PalZ* 94(3): 413–29. DOI:10.1007/S12542-020-00522-X.

He, Shuhang. 2017. “Responding to Funding Cuts as a Government-Funded Museum.” Thesis diss., University of Washington.

Hennessy, Kate. 2009. “Virtual Repatriation and Digital Cultural Heritage: The Ethics of Managing Online Collections.” *Anthropology News*. 5-6.

Hirshon, Nicholas. 2018. “Digital Archive of ONE National Gay and Lesbian Archives.” *American Journalism Historians Association*. 35(1): 121–125 DOI: 10.1080/08821127.2017.1419766

ICOM. 2025. “International Council of Museums.” Effective March 2025. https://icom.museum/en/.

iDigBio. 2024. “About iDigBio.” Effective May 2024. https://www.idigbio.org/about-idigbio.

IPT. 2025. “IPT: The Integrated Publishing Toolkit.” Effective March 2025. https://www.gbif.org/ipt.

Johnson, Erynn H. and Carter, Aja M. 2019. “Defossilization: A Review of 3D Printing in Experimental Paleontology.” *Frontiers in Ecology and Evolution*. 7(430): 1-7. DOI: 10.3389/fevo.2019.00430.

Johnson, Kenneth G., Filkorn, Harry F., Stecheson, Mary. “A Collaborative System for Sharing Paleontology Collections Data.” *Geosphere*. 1(2): 61-77. DOI: 10.1130/GES00011.1.

Johnson, Kirk R., and Owens, Ian F. P. 2023. “A Global Approach for Natural History Collections: Integration of the World’s Natural History Collections Can Provide a

Resource for Decision-makers." *Science: Natural History*. 379(6638): 1192-1194. DOI: science.org/doi/10.1126/science.adf6434.

Kaiser, Katja, Heumann, Ina, Nadim, Tahani, et al. 2023. "Promises of Mass Digitisation and the Colonial Realities of Natural History Collections." *Journal of Natural Science Collections*. 11: 13-25.

Karim, Talia S., Burkhalter, Roger, Farrell, Úna C., et al. 2016. "Digitization Workflows for Paleontology Collections." *Palaeontologia Electronica.* 19.3.4T: 1-14. https://doi.org/10.26879/566

Kim, Alexander. 2024. "The Importance of Paleontology Collections." *Park Paleontology News*. 14(1): 1.

Kjærgaard, Peter C. 2012. "The Fossil Trade: Paying a Price for Human Origins." *The History of Science Society.* 103(2): 340-355.

Krishtalka, Leonard, and Humphrey, Philip S. 2000. "Can Natural History Museums Capture the Future?" *BioScience*. 50(7): 611-617.

Lautenschlager, Stephan. 2016. "Reconstructing the Past: Methods and Techniques for the Digital Restoration of Fossils." *Royal Society Open Science*. 3(160342): 1-18. http://dx.doi.org/10.1098/rsos.160342.

Lebrun, Renaud, and Orliac, Maëva. 2017. "MorphoMuseum: An Online Platform for Publication and Storage of Virtual Specimens." *Paleontological Society*. 22: 183-195. DOI: 10.1017/scs.2017.14.

LeFebvre, Michelle J., Brenskelle, Laura, Wieczorek, John et al. 2019. "ZooArchNet: Connecting Zooarchaeological Specimens to the Biodiversity and Archaeology Data Networks." *PLoS ONE*. 14(4): 1-19.

Lendemer, James, Thiers, Barbara, Monfils, Anna K. et al. 2020. "The Extended Specimens Network: A Strategy to Enhance US Biodiversity Collections, Promote Research and Education." *BioScience*. 70(1): 23-30.

Lepore, Taormina J., Lundgren, Lisa, Lawver, Daniel. 2023. "The Impact of Field Experiences in Paleontology on High School Learners." *Journal of Geoscience Education.* 1-16. DOI: 10.1080/10899995.2023.2175525

Lewis, Dyani. 2019. “The Fight for Control Over Virtual Fossils.” *Nature*. 567: 20-23.

Lindqvist, Katja. 2012. “Museum Finances: Challenges Beyond Economic Crises.” *Museum Management and Curatorship.* 27(1): 1-15. https://doi.org/10.1080/09647775.2012.644693

Lozej, Špela Ledinek. 2020. “Collaborative Inventory-A Participatory Approach to Cultural Heritage Collections.” In *Participatory Research and Planning in Practice*, edited by J. Nared and D. Bole. The Urban Book Series.

Macdonald, Sharon. 2006. *A Companion to Museum Studies.* Blackwell Publishing.

MacFadden, Bruce J., Lundgren, Lisa, Crippen, Kent, et al. 2016. “Amateur Paleontological Societies and Fossil Clubs, Interactions with Professional Paleontologists and Social Paleontology in the United States.” *Palaeontologia Electronica*. 19.2.1E: 1-19.

Mallison aus Tübingen, Heinrich. 2007. “Virtual Dinosaurs: Developing Computer Aided Design and Computer Aided Engineering Modeling Methods for Vertebrate Paleontology.” PhD diss., Eberhard-Karls-Universität.

Marshall, C.R., Finnegan, S., Clites, E.C. et al. 2018. “Quantifying the Dark Data in Museum Fossil Collections as Palaeontology Undergoes a Second Digital Revolution.” *Biology Letters*. 14(20180431): 1-4. http://dx.doi.org/10.1098/rsbl.2018.0431.

Marty, Paul F. 2008. “Museum Websites and Museum Visitors: Digital Museum Resources and Their Use.” *Museum Management and Curatorship*. 23(1): 81-99.

Matsui, Kumiko, and Kimura, Yuri. 2022. “Museum Exhibitions of Fossil Specimens Into Commercial Products: Unexpected Outflow of 3D Models Due to Unwritten Image Policies.” *Frontiers in Earth Science*. 10(874736): 1-13. DOI: 10.3389/feart.2022. 874736.

Medina, Joshua J., Maley, James M., Sannapareddy, Siddharth, et al. 2020. “A Rapid and Cost-Effective Pipeline for Digitization of Museum Specimens with 3D Photogrammetry.” *PLoS ONE*. 15(8): 1-14. https://doi.org/10.1371/journal.pone.0236417.

Meng, Yuanliang, Li, Junyan, Denton, Patrick, et al. 2012. “IPKB: A Digital Library for Invertebrate Paleontology.” *JCDL’12.* 101-110.

Meshlab. 2025. “Meshlab News.” Effective March 2025. https://www.meshlab.net/.

Meshmixer. 2025. “Meshmixer Description.” Effective March 2025. https://apps.autodesk.com/FUSION/en/Detail/Index?id=4108920185261935100&appLang=en&os=Win64.

MorphoSource. 2024. “About MorphoSource.” Effective May 17. https://www.morphosource.org/docs/about.

Nelson, Gil, and Ellis, Shari. 2018. “The History and Impact of Digitization and Digital Data Mobilization on Biodiversity Research.” *Philosophical Transactions B*. 374: 1-9. http://dx.doi.org/10.1098/rstb.2017.0391.

Nelson, Gil, Paul, Deborah, Riccardi, Gregory, et al. 2012. “Five Task Clusters That Enable Efficient and Effective Digitization of Biological Collections.” *Zookeys.* 209:19-45. DOI: 10.389/zookeys.209.3135.

NetX System. 2025. “Not Just Another D.A.M. Company.” Effective March 2025. https://www.netx.net/company/.

NoCTURN. 2024. “About NoCTURN.” Effective May 16. https://nocturnetwork.org/organization-structure-of-nocturn/.

Norris, Christopher A., and Butts, Susan. 2014. “Opinion: Let Your Data Run Free? The Challenge of Data Redaction in Paleontological Collections.” *Collection Forum*. 28(1-2): 113-118.

Oosthuizen, Majola J. H. 2002. “Action Research.” In *Topics in Australasian Library and Information Studies, Research Methods for Students, Academics and Professionals (Second Edition).* edited by Kirsty Williamson, Amanda Bow, Frada Burstein, et al. Chandos Publishing. https://doi.org/10.1016/B978-1-876938-42-0.50017-4.

Otero, A. Moreno, Falkingham, A.P., Cassini, P.L. et al. 2020. “Three-dimensional Image Surface Acquisition in Vertebrate Paleontology: A Review of Principal Techniques. *Publicación Electrónica*. 20(1): 1-14.

Page, Lawrence M., MacFadden, Bruce J., Fortes, Jose A., et al. 2015. “Digitization of Biodiversity Collections Reveals Biggest Data on Biodiversity.” *Oxford Journals*. 65(9): 841-842.

Park, Juhee. 2021. “An Actor-Network Perspective on Collections Documentation and Data Practices at Museums.” *Museum & Society*. 19 (2): 237 - 251.

Pellens, Roseli. 2022. *Natural History Collections in the Science of the 21st Century: A Sustainable Resource for Open Science.* John Wiley & Sons, Inc.

Pérez-Ramos, Alejandro, Figueirido, Borja. 2020. “Toward an ‘Ancient’ Virtual World: Improvement Methods on X-ray CT Data Processing and Virtual Reconstruction of Fossil Skulls.” *Frontiers in Earth Science.* 8(345): 1-23. DOI: 10.3389/feart.2020.00345.

Peters, Shanan, Zhang, Ce, Livny, Miron, et al. 2014. “A Machine Reading System for Assembling Synthetic Paleontological Databases.” *PLoS ONE*. 9(12): 1-22. DIO: 10.1371/journal.pone.0113523.

Quigley, Aisling. 2009. “Striving to Persist: Museum Digital Exhibition and Digital Catalogue Production.” PhD diss. University of Pittsburgh. Proquest (13861836).

Rahman, Imran A., Adcock, Keith, Garwood, Russell J. 2012. “Virtual Fossils: A New Resource for Science Communication in Paleontology.” *Evo Edu Outreach.* 5: 635-641. DOI 10.1007/s12052-012-0458-2.

RapidWorks. 2025. “Rapid Works: What can you do.” Effective March 2025. https://rapidworks.eu/.

Rayfield, Emily J., Theodor, Jessica M., Polly, P. David. 2020. “Fossils from Conflict Zones and Reproducibility of Fossil-Based Scientific Data.” *SVP: Society of Vertebrate Paleontology.* 1-5.

Reed, Denné, Barr, W. Andrew, McPherron, Shannon P. et al. 2015. “Digital Data Collection in Paleoanthropology.” *Evolutionary Anthropology.* 24: 238-249. DOI: 10.1002/evan.21466.

Rodrigues, Lucas Siqueira, Nyakatra, John, Zachow, Stephan, Israel, Johann Habakuk. 2023. “Design Challenges and Opportunities of Fossil Preparation Tools and Methods.” *KUI’23.* https://doi.org/10.1145/3623462.3623470.

Ronchi, Alfredo M. 2009. *eCulture: Cultural Content in the Digital Age.* Springer. 1-465.

Rücklin, Martin, Donoghue, Philip C.J., Cunningham, John A. et al. 2014. “Developmental Paleobiology of the Vertebrate Skeleton.” *J Paleontol.* 88(4): 13-107.

ScanStudio. 2025. “ScanStudio A0.” Effective March 2025. https://www.zeutschel.de/en/produkte/scanstudio-a0-2/

Sendino, María Consuelo. 2009. “KE EMu and the Future for Natural History Collections.” *Collections: A Journal for Museum and Archives Professionals*. 5(2): 149- 158.

Seung, Choi, Park, Yong, Moreno-Azanza, Miguel. 2024. “Protocol for Electron Backscatter Diffraction (EBSD) Analysis of Fossil Eggshells.” Journal of Vertebrate Paleontology. 43(6): 1-12. DOI: 10.1080/02724634.2024.2363210.

Shaby, Neta, Assaraf, Orit Ben-Zvi, Tal, Tali. 2017. “The Particular Aspects of Science Museum Exhibits That Encourage Students' Engagement.” *Journal of Science Education and Technology.* 26(3) 253- 268.

Silva Mano, Andre da, Silva, Bruno Camilo, Mocho, Pedro, Ortega, Francisco. 2024. "Location-Based Management of Paleontological Collections using Open Source GIS Software." *Geoheritage*. 16(38): 1-16. https://doi.org/10.1007/s12371-024-00941-1.

Simmons, John E. 2015. “Collection Care and Management: History, Theory, and Practice.” In *The International Handbooks of Museum Studies: Museum Practice*, edited by Conal McCarthy. John Wiley and Sons, Ltd. 221- 247.

Sketchfab. 2025. “SketchFab Explore.” Effective March 2025. https://sketchfab.com/enterprise?ref=header.

Smith, Megan Hathaway. 2010. "A Necessary Duty, A Hideous Fault: Digital Technology and the Ethics of Archaeological Conservation." Thesis diss. Texas A&M University. Core.ac.uk.

Smith, Nicholas E., and Strait, Suzanne G. 2008. "PaleoView3D: from Specimen to Online Digital Model." *Palaeontologia Electronica.* 11(2): 1-17. http://palaeo-electronica.org/2008_2/134/index.html.

Smithsonian. 2024. “Terms of Use.” Effective May 25. https://www.si.edu/termsofuse#:~:text=The%20Smithsonian%20(and%20those%20authorized,have%20the%20rights%20to%20post.

Srinivasan, Ramesh, Boast, Robin, Furner, Jonathan, et al. 2009. “Digital Museums and Diverse Cultural Knowledges: Moving Past the Traditional Catalog.” *The Information Society: An International Journal*. 25(4): 265-278. https://doi.org/10.1080/01972240903028714.

Stiemerling, Oliver, and Cremers, Armin B. 2023. "A Paleontological Perspective on Designing Adaptable Software Systems." *Research Gate*.

Sutton, Mark D., Garwood, Russell J., Siveter, David J., and Siveter, Derek J. 2012. "SPIERS and VAXML; A Software Toolkit for Tomographic Visualisation and a Format for Virtual Specimen Interchange." *Palaeontologia Electronica.* 15(2): 1-15.

Sutton, Mark, Imran, Rahman, and Russell Garwood. 2016. “Virtual Paleontology- An Overview,” *The Paleontological Society Papers.* 22: 1–20. https://doi.org/10.1017/scs.2017.5.

Tang, Muh-Chyun. 2005. "Representational Practices in Digital Museums: A Case Study of the National Digital Museum Project of Taiwan." *The International information and Library Review.* 37: 51-60. doi:10.1016/j.iilr.2005.01.003.

Tennant, Jonathan P. and Lomax, Dean R. 2019. "An Overview of Open Access Publishing in Palaeontology." *Palaeontologia Electronica.* 1-10. https://doi.org/10.26879/968.

Uhen, Mark D., Barnosky, Anthony D., Bills, Brian, Blois, Jessica, Carrano, Matthew T., Carrasco, Marc A. et al. 2013. "From Card Catalogs to Computers: Databases in Vertebrate Paleontology." *Journal of Vertebrate Palentology*. 33(1): 13-28. DOI: 10.1080/02724634.2012.716114

Valev, Iliya. 2016. “Digital Archive of Soldiers' Legacy of the Socialist Period.” *Digital Presentation and Preservation of Cultural and Scientific Heritage*. 6: 289-292.

Valle Melón, José M., Rodríguez Miranda, Álvaro, Pérez-Lorente, Félix, et al. 2019. "The Use of New Web Technologies for the Analysis, Preservation, and Outreach of Paleontological Information and its Application to La Rioja (Spain) Paleontological Heritage." *Palaeontologia Electronica.* 22.1.1T 1-10. https://doi.org/10.26879/918.

VG Studios. 2025. “VGStudios: The Simple Solution for the Visualization of CT Data.” Effective March 2025. https://www.volumegraphics.com/en/products/vgstudio.html.

Vollmar, Ana, Macklin, James A., Ford, Linda S. 2010. "Natural History Specimen Digitization: Challenges and Concerns." *Biodiversity Informatics*. 7: 93-112.

Whitaker, Anna F. and Kimmig, Julien. 2020. "Anthropologically Introduced Biases in Natural History Collections, with a Case Study on the Invertebrate Paleontology Collections from the Middle Cambrian Spence Shale Lagerstätte." *Palaeontologia Electronica*, 23(3): 1-58. https://doi.org/10.26879/1106

White Matt, A., Campione Nicolás E. 2021. "A Three-dimensional Approach to Visualize Pairwise Morphological Variation and its Application to Fragmentary Palaeontological Specimens." *PeerJ.* 9(10545): 1-25. DOI 10.7717/peerj.10545

Wilkinson, Mark, Dumontier, Michel, Aalbersberg, Ijsbrand, Aalbersberg, et al. 2016. "The FAIR Guiding Principles for Scientific Data Management and Stewardship." *Scientific Data*. 3(60018). https://doi.org/10.1038/sdata.2016.18.

Winkler, Kevin. 2004. "Natural History Museums in a Postbiodiversity Era." *BioScience*. 54(5): 455-459.

Woodward, Simon. 2012. "Funding Museum Agendas: Challenges and Opportunities." *Managing Leisure*. 17: 14-28. http://dx.doi.org/10.1080/13606719.2011.638202.

Yale Peabody Museum. 2024. "Yale Peabody Museum Loan Policy." Effective August 2024. https://peabody.yale.edu.

Yale Peabody Museum. 2024. "Yale Peabody Museum Electronic Collections Databases Policy." Effective August 2024. https://peabody.yale.edu.

Yan, Guo and Xin, Hong. 2022. "Practical Research on Artificial Intelligence Algorithms, Paleontology, Data Mining, and Digital Restoration of Public Information." *Computational Intelligence and Neuroscience*. 2022(1): 1-7. https://doi.org/10.1155/2022/3068686

Yu, Congyu, Qin, Fangbo, Watanabe, Akinobu, Yao, Weiqi, Li, Ying, Qin, Zichuan et al. 2024. "Artificial Intelligence in Paleontology." *Earth-Science Reviews*. 252. 1-15. https://doi.org/10.1016/j.earscirev.2024.104765.

Zaidi, Syed Ahmed Jawwad. 2016. "Gamification as a Strategy to Improve User-Experience with Interactive Museum Exhibits." Thesis diss., Middle East Technology University.

Ziegler, Alexander, Ogurreck, Malte, Steinke, Thomas, Beckmann, Felix, Prohaska, Steffen, and Ziegler, Andreas. 2010. "Opportunities and Challenges for Digital Morphology." *Biology Direct*. 5(45): 1-9.

Zylberberg, Louise and Laurin, Michel. 2011. "Analysis of Fossil Bone Organic Matrix by Transmission Electron Microscopy," *Elsevier Masson SAS.* 10: 357-366.

4D. 2025. “4D: About Us.” Effective March 2025. https://us.4d.com/about-us.