Fall 2021

The Future of Fossils: The Evolution of Paleontological Research in the Modern Age

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The Evolution of Paleontological Research in the Modern Age

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An Honors Thesis Submitted in Partial Fulfillment of the Requirements for Graduation from the Western Oregon University Honors Program

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Fall 2021

Acknowledgments

Thank you to all of the professionals who took time to respond to my questions about working in the field of paleontology and what they do in their daily job. Dr. Mathew Carrano, Jean-Pierre Cavigelli, Dr. Don Henderson, Kathy Hollis, Holly Little, Dr. Susannah Maidement, Michelle Pinsdorf, and Angela Reddick all provided helpful insight to the field of paleontology from the perspective of working with museums.

I would also like to thank my advisors Dr. Amy Harwell, Dr. Gareth Hopkins, and Dr. Gavin Keulks for their continual support and encouragement throughout this project, especially through COVID and the year of virtual learning.

A special thanks to Magen Boegli for keeping me motivated to work on this thesis.

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Abstract

Dinosaurs are awesome. They hold a special place in everyone's childhood, and new discoveries in what they looked like and how they lived and might have behaved are exciting news. It's more common to come across an article unveiling a new fossil as opposed to novel breakthroughs in understanding the paleobiology of these organisms. Although discoveries in the research field are less widespread than field discoveries and new dig sites, even though the datapool of fossils grows every year, new advances in technology allow for new analytical methods to study these fossils. Researchers are now able to test a wider range of more specific hypotheses. Scientific understanding of dinosaurs and how they lived has not progressed as rapidly as would be expected in the new digital age given the abundance of fossils to study.

Paleontology is commonly thought of as digging in the field, piecing bones together in a museum, and analyzing morphological characteristics of bones to describe new species. With the new digital age and the development of many distinctions within helpful fields, such as histology, how people think about paleontology and the ways it's explored can be expanded from just dig sites to include the laboratory setting where even more discoveries happen.

Within the professional world of paleontology, there is a lot of discourse over how the field is changing, integrating new technologies, and adapting to be more efficient to researchers in the future. However, amateurs may not be aware of this discussion. My project is designed to investigate what the modern paleontologist does, articulate obstacles the field currently faces, address the plausible solutions that are being, or can

be, integrated into the field, and finally to create an online resource for aspiring paleontologists.

Definitions and Terms

Archosaur -- a phylogenetic group that includes dinosaurs, pterosaurs, crocodilians, and birds.

Chirality -- a molecule is considered chiral if it cannot be superimposed onto a mirror image of itself even if rotated or translated.

Dinosauria -- a phylogenetic group that includes dinosaurs and birds.

Eukaryotes -- multicellular life forms.

Fossils -- traces of life that have been preserved in rock material or replaced by rock material. Burrows, footprints, old seashells, amber, and dinosaur bones are all examples of fossils.

Molecular fossils -- traces of organic material that has been preserved in a fossil and may have gone alteration. DNA/RNA, proteins, carbohydrates, and lipids are examples of molecular fossils.

Morphology -- pertaining to the study of body form and anatomical features.

Paleontology -- the study of prehistoric life history based on physical evidence left behind in the form of fossils.

Petrologist -- someone who studies rocks and their composition, texture, structure, and formation.

Phylogeny -- referring to evolutionary relationships between groups of organisms.

Prokaryotes -- single celled life forms including bacteria and archaea.

Taphonomy -- the study of how organisms decay and fossilize.

Taxonomist -- someone who specializes in describing and classifying organisms.

Thin Section -- a very thin, usually 0.03mm, slice of material rock studied under a microscope.

Driving Goals

The overall goal of this thesis is to compile an online resource to encourage amateur and aspiring paleontologists to broaden their interpretation of what paleontologists do and articulate current obstacles in the field and how they are being addressed or could be addressed.

My final product will be a review and perspectives paper on the current challenges in the field of paleontology and a website oriented toward students exploring a possible career in paleontology. I want the website to serve as a means to introduce the methods used to study fossils, what those methods can tell researchers about dinosaur biology, and to provide a way for people to get involved in the community by providing links to helpful resources. I would also like the website to contribute to the discussion about progressing research within the field of paleontology.

This review and perspectives paper will cover the following driving goals:

1. A reflection on the techniques used to study dinosaur fossils.
    a. How are fossils analyzed in the laboratory setting?
    b. How are fossil collections cared for in museums?
    c. What are some current foci of paleontology?
2. Articulate current obstacles I have found and that professionals have expressed about the progression of the field of paleontology.
    a. How is the field changing as a result of the digital age?
    b. How are different fields of study integrated to improve how fossils are analyzed and studied?

3. Identify solutions either currently being implemented or ones that could be implemented in the near future.
    a. How can more people get involved?
    b. How can the research community integrate different fields to further progress research?
    c. What should aspiring paleontologists be aware of as they prepare a career or serious hobby in the field?
        - Concise advice and resources for aspiring paleontologists.
            - How hard can it be to become a paleontologist?

The website I produce in conjunction with this paper will include tabs and links that refer to these driving goals. I have outlined in the Methods section how these goals are incorporated into each tab of my online resource.

Methods

The first part of this project was to research and become familiar with techniques used to study and analyze fossils. Using online resources, published studies, and conversations with professionals in the field. I gathered information regarding the variety of the most useful and common techniques used in fossil analysis today. This culminated in my “Modern Techniques” section below. Where possible, research was focused on dinosaur fossils, but I accepted techniques published on other paleofauna that could be applied to dinosaur fossils. I began by researching practices in fossil analysis in the laboratory setting and the contribution of those practices. My focus was on the methods used for morphological, microscopic, molecular, chemical, and histological analyses. This is not a comprehensive list of all research methods, but ones I thought were important and show promise of advancing paleontological research in this increasingly digital age. The goal of this research was to understand why these tests are important to understanding how the organism lived and what each technique specifically tells scientists about the organism’s biology, rather than an explanation on the technology behind those tests.

I also contacted museums known for their dinosaur collections, such as the Smithsonian Institute and the Wyoming Dinosaur Center, and asked their respective staff how fossils are stored, prepared in their care, studied in their labs, and prioritized for analysis. Insight I received from professionals was organized into the “Modern Techniques” and “Role of Museums” sections where appropriate. While in contact with the museums mentioned above, I inquired about how they maintain their collections that are not on display, how many of their fossils have been analysed, how many have been in storage since their excavation, what their plans are for their fossils in long-term storage, and how often they acquire new fossils. I contacted professionals in three common roles in museums: collections manager, curator, and researcher. I also asked questions specific to their everyday jobs, fossil collections, volunteer programs, digitizing projects, research studies, and opinions on the future of the field. Few professionals were asked the same questions as I tried to personalize each email based on their job description and areas of interest where they were posted. I have collected samples of the initial emails into "Appendix A: Sample Emails" at the end of this paper.

The second part of this project was researching the ongoing conversation in the paleontological community about the future of the field. Discourse about the future of a field is common, especially by those active in said field. Through online journals, such as Palaeontologia Electronica, I read about the opinions of professionals in articles geared toward their peers about the future of the field and their expectations of various pertinent aspects. Paleontologists have been discussing technological and societal obstacles for a long time. This constant awareness and reflection of modern obstacles and future changes has kept the field relevant and useful in the exploration of prehistoric life. I included a discussion by Lipps written in 2007 as a way to gauge what change was expected, where we currently stand, and take that into consideration when developing expectations for the next 10 years. I chose Lipps because his paper included many things I saw being discussed in other articles and many of his points are still relevant to today.

The final part of this project produced an online resource for aspiring paleontologists to inform them of the different ways dinosaur fossils can be studied, the changes happening in the paleontological field in museums, and the different ways they can get involved either through volunteering or through higher education. The website includes information pertaining to the driving goals I outlined earlier. There are six main pages on the website:

1. An overview of the history of paleontology.
    a. This pertains to driving goal #1.
2. Lab methods of paleontology including what equipment is used and how it is used and what data it tells us about the fossil and how we interpret that data into the biology of the organism.
    a. This pertains to driving goal #1.
3. Field methods of paleontology, including how to prepare for a dig.
    a. I used my own experience here as well as advice from professionals.
    b. This pertains to driving goal #2.
4. Discussion of the future. This will encompass current dilemmas in paleontology that stagnate the progression of the field, how they're being addressed, and how the new generation of paleontologists can combat this issue as they prepare to enter the field.
    a. This pertains to driving goals #2 and #3.
5. Ways to get involved. Information about various associations and organizations people can join to become part of a community to network and get hands-on experience and participate.
    a. This will also include various roles that are important to the field of paleontology and the careers associated with them.

b. Information on scientific journals about paleontology and websites dedicated to paleontology so that people can stay up to date.
    i. Resources I found that I think are valuable for amateur and hobbyist paleontologists.
    ii. This pertains to driving goal #3.

Overview and Brief History of Paleontology

The field of paleontology incorporates a number of branches of science such as geology, biology, and, more recently, physics and chemistry. It can also be divided into specific sub-disciplines depending on the area of study. Paleobotanists focus on the evolution and diversity of fossil plants, micropaleontologists concentrate on very small fossils like pollen and protists, and vertebrate paleontologists study the evolutionary history and biology of vertebrates, which include dinosaurs (National Geographic Society).

The study of fossils has been around since early civilizations. In the 5th century, the Greek philosopher Xenophanes observed fossil shells and fish and interpreted their presence to mean that land had been underwater when the fish and shells were deposited (Evolution and Paleontology in the Ancient World). He was not the only 5th century philosopher to observe or collect fossils. However, paleontology didn't really take off as a field of science until the Age of Enlightenment in the 18th century when science and questioning worldly observations became more acceptable (National Geographic Society). The term "paleontology" was conceived by French zoologist Henri-Marie Ducrotay de Blainville in 1834 (Shellers From the Past and Present). Many French scientists led the way in really establishing and advancing the field of vertebrate paleontology, including Cuvier, who was Blainville's predecessor, and Lamarck. The Bone Wars in the late 19th century inspired the expansion of paleontology and fossil hunting in North America (Servais et al, 2012). This began between Othniel Charles Marsh and Edward Drinker Cope. Both were born into wealthy families and spent their fortunes paying miners to give them any bones recovered at their dig sites and training the next generation of paleontologists to help them describe as many species as possible. Both men were fueled in their desire to outdo the other. Modern day celebrities such as *Triceratops*, *Brontosaurus*, and *Ceratosaurus* were discovered during this time (Switek, 2020). However, it's only been within the last 70 years that studying fossils removed from their environment can be done beyond morphological analysis or puzzle-piecing the bones together.

For the purposes of my review on modern fossil analysis, I consider modern paleontology to be techniques popularized and used commonly from the 1950s onward. I have chosen this time period because the 1950's was when radiocarbon dating was introduced and had significant impacts on geological research (Romig & Lindblom, 2016). Since paleontology is closely linked with geology, radiocarbon dating would have an impact on the study of prehistoric life along with the study of the rocks in which that evidence of life was found.

With new technological advancements comes new opportunities to improve upon and introduce new fossils analysis techniques. Paleontological research has made notable strides since its rise to popularity in the 1950s, and since paleontology encompasses so many sub-disciplines I will focus on vertebrate paleontology with an emphasis on dinosaur fossils.

Modern Techniques

As I stated earlier, I have defined "modern techniques" as methods commonly used after the discovery and popularization of radiocarbon dating in the 1950s. Most of the methods discussed are more modern than the 1950s and I tried to use methods discussed in discoveries and papers published within the last 15 years.

Functions and Influence

This section will answer the question presented by driving goal 1a, which asks about how fossils are analyzed in the laboratory setting. Techniques covered are microscopy, x-ray imaging and CT scanning, histology, biomechanical modeling, and morphological analysis. I also include volunteer programs here because they are popular in institutions for education purposes and have the capability to be used in research programs.

Microscopy is used to get a closer look at fossils to see their smaller structures or to study small fossils. There are three categories of microscopes: optical, electron/ion, and scanning probe. Optical microscopes use visible light to see things only micrometers ($10E^{-6}$m) in length. Electron and ion microscopes use a beam of charged particles to see things as small as nanometers ($10E10^{-9}$m) and angstroms ($10E^{-10}$m) in length. Scanning probe microscopes create images of surface features down to the atomic level. Optical microscopes include dissecting and compound microscopes. Dissecting microscopes allow for the observation of 3D materials while compound microscopes are used for looking at thin sections. Microscopes are common in lab rooms and for looking at very small fossils, such as teeth and scales, and surface features. Injuries in bones from teeth or claw wounds can be observed in detail by dissecting microscopes. Scanning electron microscopes allow researchers to look at the smallest structures in the bone and see traces of protein fibers similar to collagen, and blood cells (Service, 2015). One drawback for this method is the cost of the machine. Scanning electron microscope machines can cost almost one million dollars (Brake, 2010). Even paying another institution to use their machine can be expensive.

X-ray imaging allows scientists to see fossils that have not been fully exposed from the rock, while electron microscopy allows for high resolution of the surfaces of fossils (Safford, 2014). The Stanford Synchrotron Radiation Lightsource (SSRL) in California is a high-end x-ray machine that uses high energy electrons to cause elements to glow and reveal a more detailed picture of things no longer visible to the naked eye (Stober, 2009). These images also allow researchers to see details of soft tissues and filaments, such as feathers, that once surrounded the bone. Advanced technology like these machines are not always available to labs conducting research on fossils.

X-ray computed tomography, or CT scanning, is possible on fossils and is a non-destructive method of recording the fossil in a series of images (Reisz & Sues, 2015). It works by taking several images of cross sections and stacking them together to produce a 3D image of the object. This allows researchers to see internal structures, if any, without breaking open the fossil. CT scans can be used to determine how much of a fossil is still in the rock matrix without manual preparation. The ability to see internal structures and have them on a computer allows researchers to measure the volume of cavities and produce endocasts from the data (Racicot, 2017). Researchers can also get a look inside dinosaur eggs and see the development of embryos if they are fossilized (Davis, 2020).

There is one notable drawback to using this technique. CT images take up much more storage space than a series of regular images, and they don't always produce a good scan. There are several factors that can impact the quality of the scan such as the size of the fossil, the density of the rock matrix around the fossil, and metallic compositions in the rock (Panciroli, 2016).

Histology, or the study of tissues and tissue structures on the microscopic level, has helped paleontologists study growth rates and metabolic rates in extinct vertebrates (Reisz & Sues, 2015). Bailleul et al. published a paper in 2019 reviewing the evolution of histology in paleontology, focusing on fossil archosaurs with an emphasis on Dinosauria, and how histology has developed into a subfield that can answer more questions than just those surrounding skeletal tissues. For example, skull histology has illuminated oral adaptations in duck-billed dinosaurs, and the study of medullary bone presence in relation to sex, maturity, and possible pathological contamination. The authors discuss new techniques that allow for the study of soft-bodies tissues as well as feathers, skin, and ovarian follicles. Researchers use similar techniques to petrologists who look at rocks in thin-section. Unfortunately this method is destructive toward the original fossil and new technology in the future should allow for virtual histology or minimal damage to the original specimen (Bailleul et al., 2019).

Biomechanical modeling is used to explore questions about how dinosaurs lived, such as how dinosaur posture and how they moved. Based on fossils and what we know about biomechanics and physics, scientists are able to use computer programs to reconstruct muscles onto the fossil skeletons and test models made by those reconstructions. One study published in 2021 describes the process of using computer reconstruction and a spring-suspended biomechanical model to determine the walking speed of *Tyrannosaurus rex* based on the calculated frequency of the tail movements (Van Bijlert et al, 2021). They also made an animation of the dinosaur walking based on their study. Another study used *Coelophysis* locomotion as a case study to outline the process of biomechanical analysis using 3D musculoskeletal model (Bishop et al, 2021). However, these types of models based on fossilized remains come with many limitations, such as joint shape. True joint shape can be changed by the presence and shape of cartilage that has not fossilized with the bone, and taphonomic distortion. These minute differences can influence how the organism moved and held itself. Despite this and other caveats, these studies are great applications of using what scientists know about extant animal biomechanics and applying them to extinct species.

Molecular fossils, including DNA, have allowed biologists to dive into evolutionary relationships deep into the fossil record. They are not the same as physical fossils since they are altered over time from their original state into more of a biomarker. This metamorphosis can also help researchers understand the effects of chemical and geologic processes, such as fossilization, on biologic material. These biomarkers can help determine what type of organism they came from. For example, sesquiterpenes indicate a plant or insect, and steranes indicate eukaryotes (Hunter, 2013). The sediment layer that contained the fossil is also tested for these biomarkers to make sure they are exclusive to the fossil. Molecules of interest can be separated through chromatography methods and analyzed through mass spectrometry. Mass spectrometry uses the mass-to-charge ratio of molecules to determine their structure and chemical properties. Dating these fossils must be done indirectly by dating the surrounding rock and matrix (Hunter, 2013). DNA, an exciting molecular find for fans of Jurassic Park, is highly unlikely to be preserved in ancient fossils and analyses can be unreliable for specimens older than 1 million years, not to mention the potential for contamination (Schweitzer et al, 2008). Contamination can come in the form of microbial life. A study on the bones of a *Centrosaurus* specimen found that at some point the bones became a host for an environment of microbes that left behind their own molecular biomarkers including DNA (Saitta et al., 2019). Microbial contamination of fossils is out of our hands, but it can be useful in understanding the chemical alterations of biologic molecules and the conditions in which they can be preserved. The study also shows the importance of ruling out foreign biotic contamination before declaring the presence of dinosaur related molecular fossils.

Chemical analysis of fossils can include an array of types of tests and many incorporate types of microscopy, mass spectrometry, and chromatography to separate and analyze molecules and ions within the bone and surrounding matrix. Some analyses require a pretreatment of the fossil beforehand like heating up the sample such as pyrolysis gas chromatography-mass spectrometry (Schweitzer et al., 2008). As mentioned earlier, mass spectroscopy shows the mass-to-charge ratio of components in the analyzed molecule. Gas chromatography separates volatile compounds from one another. The different variations of these tests are specific ways to separate, measure, and identify biomolecules and compounds based on their physical and chemical properties. Solution-phase proton nuclear magnetic resonance measures the magnetic moment of nuclei and is useful in studying molecules like hemoglobin (Schweitzer et al., 2008). Types of spectroscopy can also be useful in identifying bond types such as carbon-carbon double bonds and hydrogen bonds in a molecule. Electron diffraction pattern analysis is used to quantify the degree of diagenetic alteration sustained by the sample through the remnants of biomarkers left behind (Schweitzer et al., 2008). These tests can be the difference between identifying melanosomes preserved in fossil bone and melanosomes produced by microbes in the fossil bone (Schweitzer et al., 2015). Melanosome shape and density can give insight on skin and filament color in dinosaurs.

Once certain biomarkers, like proteins, have been identified in the fossil bone, there are more biomolecular analytical techniques that can be done on more samples to identify their structure and identity to a more detailed extent. Amino acid analyses can describe the orientation, or handedness of amino acids, which can be useful in determining how to analyze DNA potentially found in fossils (Schweitzer et al., 2008). Other analyses include immunoblots and electrophoresis, specific enzyme degradation, and antigen-antibody interaction analysis which are also described in the 2008 paper by Schweitzer et al. Even though these methods are destructive to the sample, they are important to identifying biomolecules in the fossil that can contribute to our understanding of phylogenetic and evolutionary relationships between extinct and extant groups.

Morphological comparison is one of the most useful and popular modes of fossil identification. It is easy to use in the field and in the lab because all that it requires is knowledge or a reference. Morphology is the study of forms of things, so morphological comparison is comparing the forms and structures of found fossils to known fossils and bones to determine if it is a new species or a new individual of a known species. These structures are also compared to extant species to infer possible purposes and phylogenetic linkages. It is a skill that in theory requires education and experience, but a study conducted by Butler et al. in 2020 evaluated the usefulness of visual aids in helping volunteers identify fossils similarly to professionals. One group was composed of people who were trained and experienced in fossil identification. Two groups of volunteers had varying education levels and were tasked with identifying certain fossils based on the keys they were given. There were three different types of keys used with the only difference being the types of images included as a visual aid. This study suggests that there is a way to use volunteers, most of whom were teenagers, to help with accurate fossil identification similar to professionals. This study may represent the beginning of developing a method to allow volunteers to aid in accurate fossil identification. This study was done by Montana State University, but there are many institutions, most notably museums, that already use volunteers to their advantage.

Volunteers are not always the best option for every situation. Ms. Angela Reddick at the Wyoming Dinosaur Center clarified the difference between volunteers and guests who pay to experience work in the lab or field. She defined volunteers as people who can spend around 8 hours a day for at least one week in the lab. Their Paleo Prep and Dig for a Day programs allow participants to be in the lab for a day and work on fossil preparation. Although it can be helpful in getting work done that employees don’t have time for, it’s not very efficient. Regardless, these programs are not about efficiency but about allowing interested parties a chance to learn about the field and what professionals do as part of their job.

Areas for Improvement

This section will answer the question presented by goal 2b which asks how different scientific fields are, or can be integrated, when studying paleobiology from fossils.

There's only so much one can learn from observing fossils with the naked eye, so techniques that look at microstructures in various ways are increasingly more helpful in answering questions about dinosaur biology. These microstructures can include cells, organelles, such as melanosomes, and the structures of proteins. The progress of our understanding of microscopic structures associated with dinosaur fossils is limited by what technologies allow researchers to observe. With the increase in advanced equipment that can see the smallest of structures and trace structures, paleontologists can use the same machines to answer different questions related to soft tissues or soft tissue traces. Not all fossils are suitable for microscopic analysis, but it currently is the most useful strategy for studying fossils in great detail.

The electron microscope was first invented in 1931 - 90 years ago (Smith, 2018)! The improvement in resolution that has been achieved in almost 100 years is promising if that trend can continue into the future. I'm not sure what kinds of new or improved microscopes will be developed in the future beyond higher resolution images. Either way, people who specialize in different fields such as paleobotany or microbiology are most likely using the same machines in their studies, and these images gathered for one study may be very useful in another study without having to transfer the fossil for rescanning. I'm hoping the future of electron microscopes and CT scanning will allow histologists to study soft tissues in a less or non-destructive manner so the original fossil can be reproduced.

In the *Coelophysis* biomechanical modeling study mentioned earlier, the researchers used a digital skeleton-to-computer model technique which was developed and used in multiple studies of extant species (Bishop et al., 2021). They also recognize that since the foundation of their model was based on studies for extant species, further studies of extant species of both arcosaurs and non-archosaurs will allow for more accurate modeling of extinct species. In particular, more information needs to be gathered on "relating muscular anatomy to function" and "how long muscle fibers need to be to be able to effectively execute movement over a range of postures." (Bishop et al., 2021). The study ends with a note about moving forward and taking these model simulations with scrutiny since they are simplified and not exact models of reality. They are helpful guides and can be stepping stones to future studies exploring similar themes in paleobiology.

Similarly to the use of microscopes and biomechanical modeling, techniques used for chemical analyses are limited by current technology and understanding of biomolecules and how they degrade over time. There's not much that can be done about the destructiveness or monetary cost of these methods, but sacrificing samples or fossil remains must be made for the progress of our insight to dinosaur biology and evolutionary relationships.

The most constructive improvement of these techniques is to integrate them into a study. Integrating two or more of these methods can do wonders to advance our understanding of dinosaurs. An example of where integration of several methods has made immense progress in the field is with *Spinosaurus*. Using biomechanical models of different tail shapes and morphological comparisons to extant aquatic vertebrates, the tail of *Spinosaurus* was larger than previously thought and used to propel the dinosaur through the water (Ibrahim et al., 2020). This study supports *Spinosaurus* being an aquatic predator. Now, one of the most iconic theropods has a new look to match the latest skeleton and to show our understanding of the function of its anatomy. The future of integrating techniques has the power to change the shape of dinosaurs we thought we knew.

Role of Museums

There's no doubt natural history museums play a crucial role in research, specimen conservation, and public education. They are not the only institutions who conduct research on paleobiology or house fossil collections, but I have chosen to focus on them because they tend to hold larger collections than universities alone and aid in research of many universities and other museums.

Functions and Influence

This section will answer the question presented by goal 1b which asks how museums care for their fossil collections. There are three main roles for professionals who work with fossils in museums: collections managers, curators, and researchers.

Collections managers oversee the proper care, storage, and record-keeping of items. They also determine items of interest to the museum and items that should be removed from the museum. With the arrival of the digital age and the tendency for record keeping to move online, some institutions are beginning or are currently in the process of moving all collections records into an online database. This shift from physical copies to digital entries is called digitization.

Curators govern the museum exhibits and visual displays, and often aid in building collections in a specific area of interest.

Researchers conduct studies on items in collections for scientific understanding and later publication. They are not limited to only the fossils in the collections of their respective museums, but can study items from other museums through working with the curators and collections managers there. Dr. Matthew Carrano at the Smithsonian

Museum of Natural History informed me that loaning materials can be a challenge due in part to their fragility, so they allow people to study materials in a workspace in the collections area. Most requests to borrow materials nowadays are for CT scanning. Researchers can specialize or utilize any of the techniques for fossil analysis discussed previously and publish their findings through a scientific journal.

Digitizing fossils is a fairly new method of record-keeping that many institutions are shifting toward to expand access to their collections. Darwin Core is a database which is modeled off of Dublin Core, the library standard. It is a set of terms that the community has agreed upon that accompany a fossil record, such as species name and locality, and can include hundreds of fields per record. Some collections management database softwares include EMu, IDigBio, and GBIF. EMu is an electronic museum run by Axiell and is not specific to sciences. IDigBio stands for integrated digitized biocollections and is funded by the National Science Foundation. It is specific to biology and paleobiology collections and their goal is to facilitate the digitization of biological collections across the US to make them more accessible to everyone. GBIF, which stands for global biodiversity information facility, is a network that uses data standards like Darwin Core to store information about recorded species in institutions across the world and keeps that information accessible internationally.

Ms. Kathy Hollis, who is a collections manager at the National Museum of Natural History at the Smithsonian Institution, informed me that in-house researchers keep their records in an independent database which is transferred to a team for integration into EMu. It's estimated 14 million records need to be digitally cataloged to account for their entire collection.

Museums also function as education centers for the public. Many have programs where people can pay to participate and learn about fossils and prepare fossils while whittling away at the work left for volunteers and employees. These programs are good money for the institution, and also provide an entertaining environment for people to learn about paleontology while getting first hand experience which fosters appreciation for the time and effort it takes to prepare collections.

Areas for Improvement

This section will address the questions presented by goal 2a which asks how the field is adapting to the digital age. I define obstacles as hindrances that can be mitigated by the researcher(s). Therefore, most fossils only being fragments is not an obstacle because that is out of the control of the researcher, but that can contribute to an obstacle such as defining what one “lot” is. One “lot” can refer to one specimen or it can refer to a tray of fossils from the same locality. This is an important term to define for developing universal standards in digitized collections.

Ms. Kathy Hollis, the paleobiology collections manager at the National Museum of Natural History at the Smithsonian Institution, offered insight on solutions to different specializations that will be valuable in fossil record keeping. There is a need for trained taxonomists to be able to identify fossils through images. With varying success Ms. Hollis has been working in developing ways taxonomists can work remotely with images of fossils instead of the physical specimen. Information science, or library science, is another imperative role in data stewardship where it’s important to understand how fossils can be translated into a data point useful for analysis. These data points for analysis can avert recurrence issues in publication research. About 20 years ago a paleobiology database was established based on publications, but since many fossils recur in multiple publications and some in none at all, it was a biased database. Now, it's a lesson to avoid in current paleobiology databases. Volunteers, even without extensive training, can be useful in the digitizing process by transcribing labels into the virtual database. This is not a plug-and-chug solution as there will still need to be training in using the virtual system, but once established this can be done by multiple people remotely and accelerate a part of the digitization process.

Discussion of the Future

Modern Techniques

Advancements in paleontology can be directly linked with access to better equipment and studies on extant species. This trend will no doubt continue into the future, but it's difficult to judge how it will change and add to our ability to research these fossils in greater detail. I look forward to seeing how microscopes, biomechanical modeling, and molecular and chemical analyses will give us a more detailed look at soft tissues, microstructures, biomolecules and expand the types of questions about them that can be explored.

Further studies of extant species on how their bones, muscles, and joints relate to their movements and muscle limitations can help improve models used to study similar questions about dinosaurs. The 2021 study by Bishop et al. acknowledged how biomechanic models used in studies of extant species was necessary for their own research of *Coelophysis* and how further use of these models on extant species will benefit the exploration of these models for extinct species. Without the understanding of how certain biomechanical processes work today, there is no understanding of how they may have worked over 65 million years ago. This is a great example of how biologists studying today's vertebrates can create resources to help paleobiologists. Another example of how modern biologists can help is through the study of microbiology. Understanding microbial life, how it can affect its immediate environment, and how it can be preserved in bone and sediment can help differentiate between biologic molecules that were derived from the fossil bone of interest and those molecules derived from contamination by other organisms.

Molecular paleontology and the understanding of how biomolecules degrade and alter over geologic time is an important field to our understanding of what biomarkers, such as amino acids, proteins, carbohydrates, and lipids, can tell about a fossil specimen and its phylogenetic relationships to other animals (Schweitzer, 2002). There are a plethora of different ways to identify and analyze biomolecules in a sample and there's no "best practice" when they are all subjective to the type of biomolecule being studied. Organic chemistry is a highly valuable field to put time, money, and resources into to test hypotheses related to fossilization, preservation and deterioration of organic material, and evolutionary relationships. As the equipment and techniques used in organic chemistry outside of paleontology advances, so too will the ways these techniques can be applied to examine fossil specimens.

Most techniques are not destructive to the original specimen, but all specimens have a potential to get damaged while being studied physically. Minimizing the use of destructive techniques when necessary is a priority among everyone. Storage can also be destructive if the specimens are not stored carefully. Fossils may be rocks, but they are rare and delicate rocks that are not easily replaceable. Digitization is a great solution for backing up fossils and 3D image data about them, and molds and casts are a great way to display them without necessarily displaying the real fossil.

The preservation of the land from which the fossils were extracted can be argued as just as important as the fossil itself because it gives environmental context to the fossil specimen (Lipps, 2007). Environmental context is very important to keep in mind while studying fossils, and I can see how this can be an issue for the future in terms of urbanization and construction developments. Fortunately, many fossil dig sites in the

United States are on private property and the landowners work with paleontologists and institutions to locate and remove fossil specimens (Layton, 2016). For hobbyists and amateurs, it is important to spread awareness of recording the locality of fossil specimens they collect even if they are not used in research or donated to a museum.

Museums and Research

One issue with fossils is that most of them are only fragments. Many fossils are pieces of a larger puzzle, and not all pieces are always fossilized together, or at all. Many museums are working toward a more digital approach to fossil research since it offers a way to meticulously study very fragile specimens. 3D printing and modeling of fossils allows scientists to manipulate the image and structure of the recovered fossil to fill in gaps or restore distortions caused by pressure over time (Safford, 2014). Volunteers could be helpful with digitizing fossils into an online database. This still takes training and getting them used to the system, but it can also be done remotely. More research is needed to develop an effective way for volunteers to help researchers with identification and digitization of fossil specimens. An issue with this could be that most people excited about fossils and wanting to help are children. However, with computer and programming skills geared toward children teaching them at a young age there is an increasing amount of children that are growing with technological knowledge and are faster learners with new computer programs. If programming code can be made simple for young children to learn, it could be possible to provide a way to teach them a simplified manner of what it means to digitize a fossil. It's just an idea, but kids are one of the easiest groups to encourage enthusiasm for dinosaurs and fossils.

Regarding students and people looking into the field as a career, “we need to direct them to opportunities other than the traditional paleontological jobs, and we need to promote the use of paleontologists in other disciplines, the environmental sciences being one of the most important” (Lipps, 2007). Expanding the idea of what a paleontologist can do can help to create more jobs in the field. If molecular biologists and evolutionary biologists can work on fossil specimens researching different questions, then that’s two different jobs working in paleontology.

Another issue regarding the future of the field is the spreading of misinformation about paleontology and the prehistoric world. Anti-science groups include the specific ideas of creationism, pseudoscience, and intelligent design that manipulate scientific evidence for their own support. I can attest from experience that creationist groups collect fossils to support their idea that the Earth is only a few thousand years old. I almost signed up as a volunteer to a fossil dig not knowing it was a creationist company going to collect dinosaur fossils from the great flood of Noah 12,000 years ago. A creationist geologist was allowed to take samples from the Grand Canyon to study the rocks from a biblical perspective after he sued the National Park Service for denying his request earlier on the basis of religious discrimination (Reilly, 2017). Not only are these institutions spreading false information to the public about the context of the fossils found, they are ignoring the science from people who have spent their lives studying fossils.

The Creation Museum in Kentucky was visited by a group of paleontologists taking a break from a conference, and “ the museum argues that the fossil record has been misinterpreted and that *Tyrannosaurus rex* was a vegetarian before Adam and Eve bit into that sin-inducing apple” (Kennery, 2009). Many of the paleontologists interviewed about the visit said at one point they worried about children entering the museum and questioning science or accepting the new “facts.” “Lisa Park of the University of Akron cried at one point as she walked a hallway full of flashing images of war, famine and natural disasters which the museum blames on belief in evolution” (Kennerly, 2009). Religion is not the enemy of science, but these institutions that spread false awareness of heavily studied subjects and undermine the work put in by geologists and paleontologists are dangerous to impressionable minds. The best that can be done to combat this is to spread awareness of actual research.

With the movement of peer-reviewed journals online and increasing access to free versions of studies, people can have easier access to actual facts, primary sources, discussions between scientists, and peer reviewed studies. I benefited tremendously from free online access to publications while doing research for this thesis. Science Direct and Palaeontologia Electronica were among the most helpful sites when it came to providing me with full articles from a variety of peer reviewed journals. Many sites, such as Google Scholar, can be helpful but they include sites that ask for money in exchange for published works. I understand paying for papers can keep a journal in business and some institutions, such as my university, will pay for an article so students can use them. However, many do not have the luxury of having a university purchase articles for them. This is why free open-access publications are important. Audiences for these articles go beyond students. It’s frustrating to come across an article about a scientific study but not being able to read the actual study apart from the abstract. Fortunately, there are numerous open access scientific journals available online. The sites that house these publications are a great way for non-professionals to stay involved in the community and the discourse between professionals. Authors are able to provide free copies of their work, so there's no harm in contacting them and asking for a copy if you're curious and want to read their study.

Another thing to keep in mind with open access publications is their ability to be translated into other languages to maximize their audience. Dr. Matthew Carrano at the Smithsonian National Museum of Natural History hosts the site Polygot Paleontologist where paleontology papers written in non-English languages are translated into English: https://paleoglot.org/. The site contains a great collection of publications written in various languages from Russian, French, and Chinese to name a few. In my research, I've come across a German paper or two that I would have used had I had a translation. This is another aspect of paleontology where professional and non-professional paleontologists can make an impact by helping to translate papers.

How Hard Can It Be To Become A Paleontologist?

There are many different ways to get into the field of paleontology, so there's no clear cut path to follow. Geology and biology are the most common Bachelor's degrees of the professionals that I contacted and spoke to. There was more variation in the Master's degrees and with some being as broad as geology to being as specific as vertebrate paleontology. There was variation with PhDs as well. So, the first step in pursuing a career in paleontology is to get a Bachelor's degree. This doesn't have to be specifically in paleontology, which allows for more flexibility in choosing a college since not everyone can afford to move to another state for several years. Computer science is a growing need in the field as it pivots towards a more digital foundation in record keeping and research. Computer skills are becoming just as important as skills with physical specimens. With all these options and diversity in choices, how do you know what university and major to pursue?

It's all about your skill set. That's common advice I've received over the past few months. You can study anywhere and be successful as long as you've built yourself a useful set of skills and knowledge for paleontology.

While I was in high school looking at colleges I came across a helpful resource at environmentalscience.org which outlined specific classes that would be most useful to me. These classes include:

- Mineralogy
- Stratigraphy
- Ecology
- Evolutionary biology
- Genetics
- Sedimentary petrology

- Vertebrate and invertebrate paleontology

General science classes such as physics, chemistry, calculus, statistics, and computer science were also recommended by the same resource. All of these recommended classes as they each offer solid background knowledge in geology and biology that overlap when studying paleontology. Computer science classes and proficiency with computer programs will be increasingly useful in the future of paleontology as specimens need to be digitized or researchers need to work with virtual fossil specimens.

While pursuing my degree, I had trouble deciding whether to major in biology or earth science and minor in the other. After looking at the specific classes required for each major, I came to the conclusion that the best way for me to get as many of those skills as possible in my toolset was to major in both and not select a minor. Later, I would try to get a chemistry minor but drop it due to the workload. During that time I took organic chemistry and that knowledge helped me understand parts of Schweitzer et al., 2008 discussing amino acid analysis. It took me five years to complete both majors, and now I have a wide background in science disciplines that I can integrate into my future studies and pursuits.

Other important skills to gain outside the classroom are field experience. Fossil digs are a great place to start. Internships and volunteer participation are great ways to get out into the field and in the laboratory with professionals and get hands-on experience with equipment. Environmentalscience.org has a whole page dedicated to agencies that provide internships although not exclusive to paleontology, the experience will certainly help in pursuing future goals.

Getting involved in associations is a great way to network and make connections with people who you may work with in the future. The North American Research Group (NARG) and the Northwest Paleontological Association are some of my local groups that hold meetings I can attend, or will be able to attend after the effects of COVID-19 settle out. These groups are also a great way to find out when and where fossil digs are occurring and get experience that way.

There are more people working in paleontology than those who actually hold the occupation title of “Paleontologist.” It’s important to note that those who hold the title are not the only people who contribute to the understanding of prehistoric life on Earth. Many fields are involved in researching the complex nature of fossilization and the secrets it contains, and the digital organization and information sharing of these specimens is just as important to aiding the progress of our understanding of these animals.

Conclusion

The paleontological community as a whole has been discussing and bringing awareness to future endeavours and ways of improvement for a long time. The field has seen massive improvements in technology which allow researchers to dive into more complex questions about dinosaur biology and provide a deeper understanding of the environment in which these animals lived. The movement of fossil specimens and published studies into the more accessible digital world is a promising step forward in making the study of prehistoric life more accessible to different branches of science.

Along with greater accessibility of fossil specimens and publications, the faster pace of online communications between paleontologists promotes easier involvement between people in different places around the world. That same fast paced communication also facilitates conversations between paleontologists and those who are curious about the field. I was surprised at how quickly I received responses from professionals I had emailed and had discussions with over the course of several weeks. Although I cannot speak outside of my own personal experience, I find it encouraging to know that there is minimal if not any gatekeeping in the paleontological community.

There are many online resources that share published studies and many associations that allow hobbyist and amateur paleontologists to get involved in their local paleontological community. I understand with the internet being such a large place that it can be difficult to get the right audience to those websites, and I have only been able to join associations I have learned about through other people. Word of mouth is still one of the most effective methods of spreading awareness about a site or group. I hope by adding my voice to the chaos of the internet I can get more relevant traffic to those sites. Moreover, I’d like to get more students and aspiring paleontologists to these helpful websites and associations so the next generations of researchers and fossil finders can be involved even before they get their degrees.

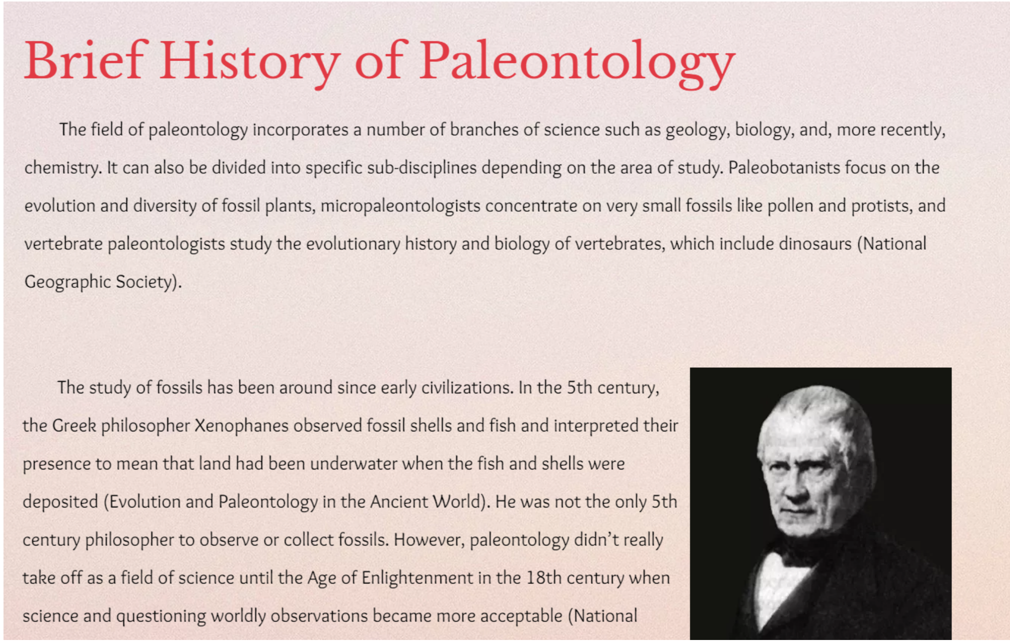
Paleontology as a science has discovered some fascinating things about dinosaurs that have completely changed the way they were seen 10 years ago. I look forward to learning what else we unearth in future years.

The Website

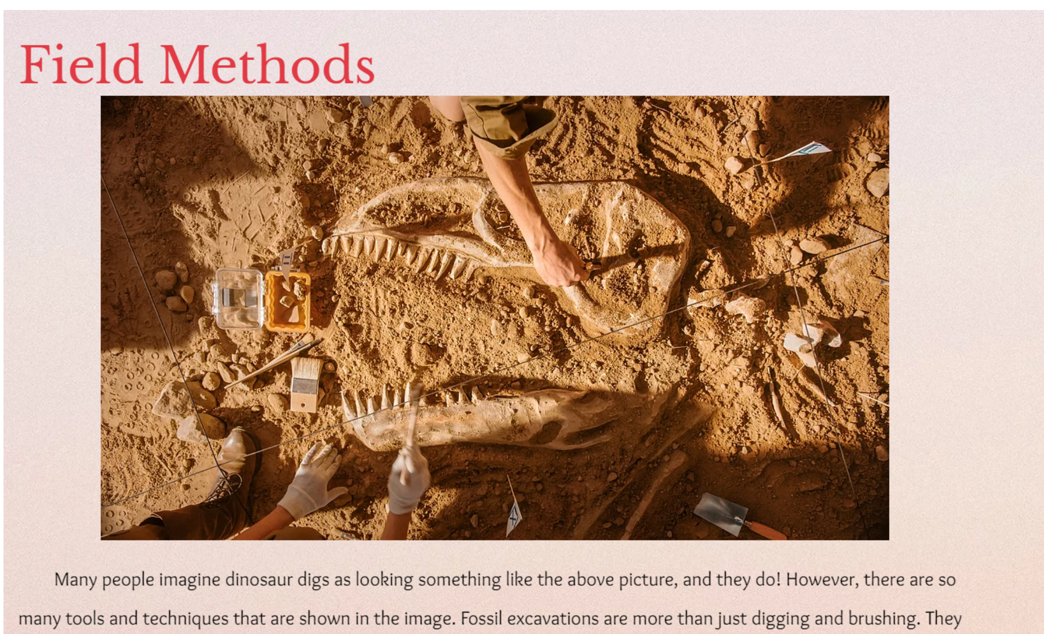
The Future of Fossils is a website designed by myself on Wix.com and can be found at https://hrmoshinsky.wixsite.com/thefutureoffossils. The purpose of this online resource is to educate aspiring paleontologists to the different fields of paleontology and to inform them of the new shift to digital fossils and information sharing. The format of the website follows the general format of the written thesis. The example images below only show the top of each page on the website.

The Home page introduces myself and the purpose of the website.

The History of Paleontology page offers a brief presentation of the history of paleontology similar to the Overview and Brief History of Paleontology section in this thesis.



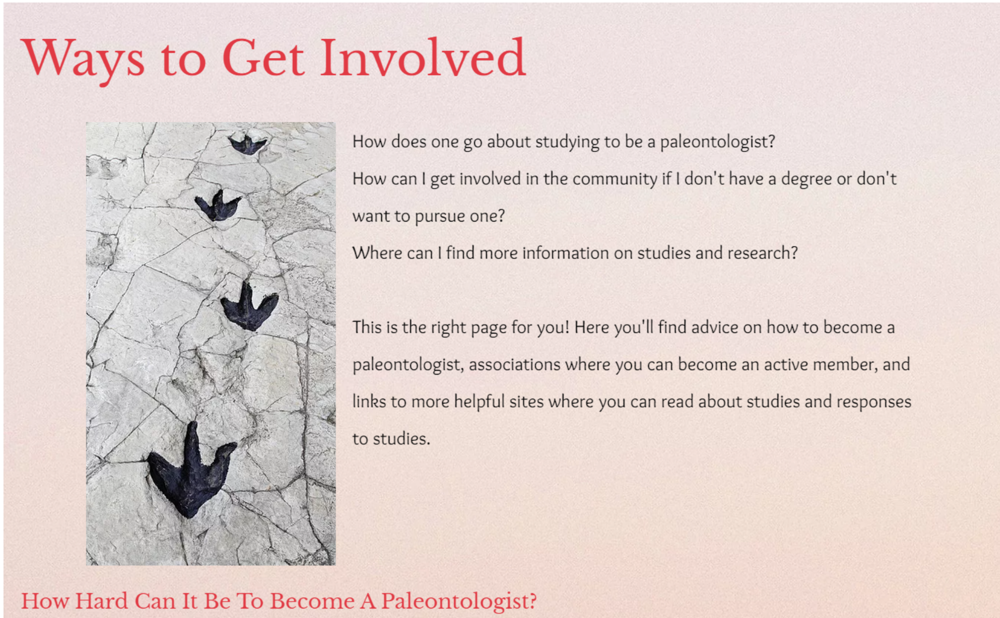
The Field Methods tab includes methods for fossil collecting, advice for going on a fossil dig, and guidance for putting together one's own fossil dig kit they make at home before embarking on an adventure.



The Lab Methods tab consists of brief descriptions of the modern techniques discussed earlier.

The Discussion of the Future tab is the same as the section in this thesis under the same name. This tab is meant to encourage aspiring paleontologists to think of the field of paleontology as many fields working together toward a common research interest.

Ways to get Involved is a page for people to find accessible online journals, publications, and associations. It includes links for helpful sites regarding education and schooling as well as links to public online journals.



Ways to Get Involved

How does one go about studying to be a paleontologist?

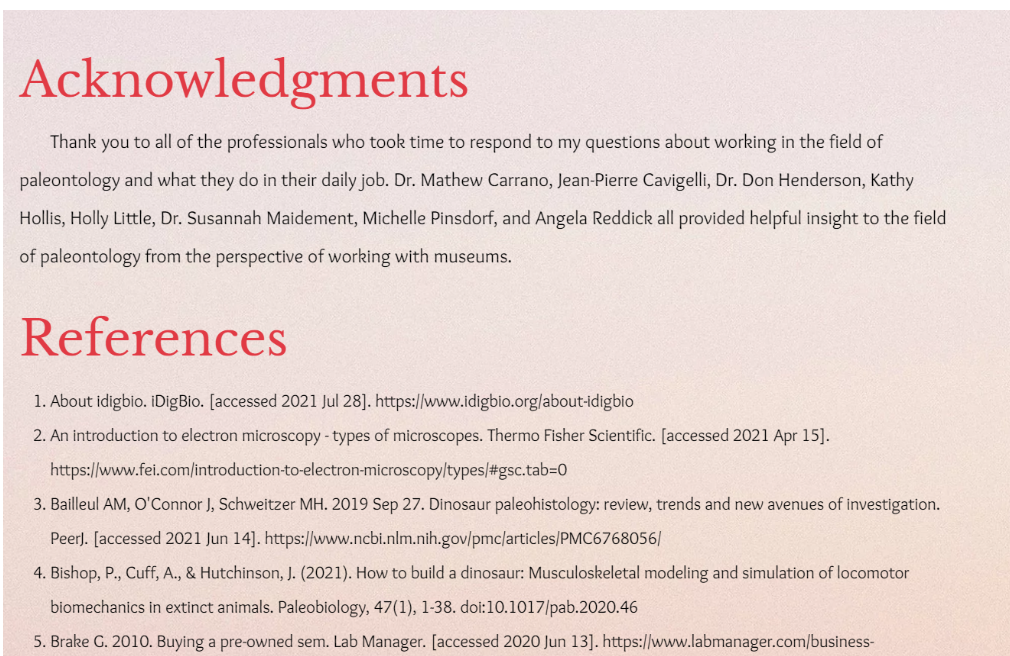
How can I get involved in the community if I don't have a degree or don't want to pursue one?

Where can I find more information on studies and research?

This is the right page for you! Here you'll find advice on how to become a paleontologist, associations where you can become an active member, and links to more helpful sites where you can read about studies and responses to studies.

How Hard Can It Be To Become A Paleontologist?

The References tab is last and includes the whole bibliography for this thesis in CSE name-year style as well as a section on acknowledgments for people I'd like to recognize in helping me finish my thesis.



Acknowledgments

Thank you to all of the professionals who took time to respond to my questions about working in the field of paleontology and what they do in their daily job. Dr. Mathew Carrano, Jean-Pierre Cavigelli, Dr. Don Henderson, Kathy Hollis, Holly Little, Dr. Susannah Maidement, Michelle Pinsdorf, and Angela Reddick all provided helpful insight to the field of paleontology from the perspective of working with museums.

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Appendix A: Sample Emails

Here I have organized five out of the ten initial emails I wrote to contact professionals. Names have been redacted for privacy, and I CC'd both my thesis advisors in the emails. Before I sent out the inquiries, I researched the people I was hoping to contact and familiarized myself with some of their work if they had published any so I could make sure I was asking relevant questions. A few who got back to me redirected me toward others in their department whom they thought would better answer my questions. The subject line of the emails was titled "Paleontological Research Inquiry."

<u>Example 1</u>

Dear [redacted],

My name is Hannah Moshinsky and I'm a student at Western Oregon University working with Dr. Amy Harwell and Dr. Gareth Hopkins on my senior Honors thesis about paleontological research.

I have some questions about how you prepare fossils and data records:

- About how long does it take to prepare a fossil specimen, and do you employ volunteers to help at any stage of the preparation?
- How are fossils kept in storage long-term maintained?
- Are you able to keep up with incoming fossils, or how do you prioritize which new fossils will be prepared first?

Thank you for your time and insight!

Sincerely,

Hannah Moshinsky

Example 2

Dear [redacted],

My name is Hannah Moshinsky and I'm a student at Western Oregon University working with Dr. Amy Harwell and Dr. Gareth Hopkins on my senior Honors thesis about paleontological research.

I have some questions about the collections access for fossils:

- How often do researchers and students ask to view and borrow fossils for their research?
- How often are new fossils or recently prepared fossils added to this program?

I also found your website on translating non-english paleontological literature to english.

- Do you also translate work from english to another language?

Thank you for your time and insight!

Sincerely,

Hannah Moshinsky

Example 3

Dear [redacted],

My name is Hannah Moshinsky and I'm a student at Western Oregon University working with Dr. Amy Harwell and Dr. Gareth Hopkins on my senior Honors thesis about paleontological research.

I understand you have published a couple works on collection assessments and are working on a digital database of fossils. I have a couple questions about your work:

- About how much of the Smithsonian's fossil specimens have been digitized?
- Is the digital database focused on researchers having access to fossil specimens without needing to see it in person, or focused as a library-like catalog of who has what specimens and their conditions?
- How do you think a digital database of fossils will impact the study of paleontology and how research is done?

Thank you for your time and insight!

Sincerely,

Hannah Moshinsky

Example 4

Dear [redacted],

My name is Hannah Moshinsky and I'm a student at Western Oregon University working with Dr. Amy Harwell and Dr. Gareth Hopkins on my senior Honors thesis about paleontological research.

I understand you work in digitizing collections and paleobiology. I have a few questions about your research:

- Do you digitize fossils as a part of your daily job?
- I read your abstract for "Establishing a New Framework for Paleontological Data Through an Evaluation of Current Data Sharing Practices" but I'm having trouble finding the actual paper. Is the framework similar to the outline in the Smithsonian Institution 3D Metadata Overview v0.6 document?
- How do you think a digital database of fossils will impact the study of paleontology and how research is done?

Thank you for your time and insight!

Sincerely,

Hannah Moshinsky

Example 5

Dear [redacted],

My name is Hannah Moshinsky and I’m a student at Western Oregon University working with Dr. Amy Harwell and Dr. Gareth Hopkins on my senior Honors thesis about paleontological research.

I have some questions on how fossils are prepared at the Tate Geological Museum:

- I understand volunteers are used to help prepare fossils for exhibits. Do volunteers remove fossils from jackets, and how are fossils prioritized for preparation?
- How often are fossils removed from jackets for preparation and research?
- About how many of the fossils collected are used in research?

Thank you for your time and insight!

Sincerely,

Hannah Moshinsky