A Rift in Our Practices?:

Toward Preserving Virtual Reality

by

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Table of Contents

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Chapter 1: An Introduction to Virtual Reality

Using technology to transport oneself into a convincing, computer-generated reality is a concept that has long been theorized in the realm of science fiction. Now, with the development and release of devices such as the Oculus Rift and HTC Vive, virtual reality is no longer just a fictional phenomenon. Though seemingly a new trend, virtual reality technology has a long and rich history that has led to its current prominence as an immersive medium for storytelling, entertainment, and a myriad of other application. Virtual reality is here, and the actions the cultural heritage community takes next will inform how VR technology is preserved, and how future users and researchers will come to understand it. This thesis will examine the history of virtual reality to contextualize its preservation, assess the current treatment of virtual reality collections in cultural heritage institutions, identify challenges preservationists will face when dealing with VR collections, and consider potential preservation strategies.

In the last few years, beginning around 2014, a plethora of new virtual reality devices has been released on the consumer market, and virtual reality, or VR, has become a buzzword as the new technology has been heavily advertised and promoted. The current wave of virtual reality devices includes the Google Cardboard and Samsung Gear VR, which can turn smart phones into virtual reality headsets, as well as the Oculus Rift and HTC Vive, which work in conjunction with powerful computers to provide more immersive and interactive VR experiences. All of these devices were released in the last three years, and many more like them have been announced by companies such as Microsoft[1] and Nintendo[2] for release in the near-future.

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[1] Paul Lamkin. "Microsoft Confirms: Xbox One VR Headset Incoming." *Forbes*. March 2, 2017. Accessed April 22, 2017. https://www.forbes.com/sites/paullamkin/2017/03/02/microsoft-confirms-xbox-one-vr-headset-incoming/#4270c3a22ea6

[2] Samit Sakar. "Nintendo 'Studying' Switch VR Support." *Polygon*. February 1, 2017. Accessed April 22, 2017. https://www.polygon.com/2017/2/1/14474524/nintendo-switch-vr-support

Although the aforementioned virtual reality headsets have recently become ubiquitous in the public consciousness and the consumer market, the technology has a decades-long history of development. This current wave of VR follows an earlier period of proliferation of virtual reality devices in the late 1980s and early 1990s. By the mid-1990s, that era of virtual reality's popularity and development had died down. The devices did not catch on as predicted and the technology disappeared from public view for several decades, until the current VR headsets came along. Given this previous boom-and-bust cycle, much speculation now exists about whether or not virtual reality will truly be a prominent medium in the future or if it will fizzle out as just another passing trend.

Regardless of virtual reality's future, artists and filmmakers are already working in the medium, and consumers are already purchasing VR headsets and playing immersive video games at home and on their cell phones. Whether or not virtual reality is here to stay, the technology has already made a significant mark on the cultural landscape at least twice in its history (in the 1990s and in the mid-2010s), and has seen wide use by artists, designers, and other creative minds, as well as by scientists and researchers. With virtual reality's history, wide range of applications, and current popularity in mind, now is the time to consider how this complex medium can be preserved for the future.

Thus far, VR has not been widely collected in cultural heritage institutions such as libraries, museums, or archives. However, as the technology becomes more pervasive and more content is created for VR platforms, institutions will need to familiarize themselves with VR and put standards in place for collecting, preserving, and providing access to virtual reality systems. This thesis will explore the challenges that cultural heritage institutions may face when dealing with collections of virtual reality and will present potential preservation strategies. Though there will be no easy solutions to the question of how to preserve virtual reality, this thesis aims to open up a conversation about handling virtual reality collections in cultural heritage institutions.

Before considering the preservation of virtual reality, it is first necessary to clarify what VR is, the kinds of content it can encompass, and the varieties of hardware systems that can be used to access virtual reality environments.

Two Spectrums: Defining Virtual Reality

"Virtual Reality" is a broad term that can be used to categorize a wide variety of diverse content types and user experiences. As such, it can be a particularly tricky concept to define. Oxford Dictionaries defines virtual reality as "The computer-generated simulation of a three-dimensional image or environment that can be interacted with in a seemingly real or physical way by a person using special electronic equipment, such as a helmet with a screen inside or gloves fitted with sensors."[3] The Merriam-Webster Dictionary defines it as "An artificial environment which is experienced through sensory stimuli (as sights and sounds) provided by a computer and in which one's actions partially determine what happens in the environment; *also*: the technology used to create or access a virtual reality."[4] Meanwhile, The Virtual Reality Society defines virtual reality as "…the term used to describe a three-dimensional, computer generated environment which can be explored and interacted with by a person. That person becomes part of this virtual world or is immersed within this environment and whilst there, is

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[3] "Virtual Reality." *Oxford Dictionaries*. https://en.oxforddictionaries.com/definition/virtual_reality
[4] "Virtual Reality." *Merriam-Webster*. https://www.merriamwebster.com/dictionary/virtual%20reality

able to manipulate objects or perform a series of actions."[5]

The first two definitions emphasize the hardware the user interacts with in order to access the virtual reality environment, while the definition from the Virtual Reality Society forgoes this distinction and emphasizes computer graphics and interactivity within a virtual environment as key features of VR. All three definitions emphasize the computer's role in generating and providing access to virtual images and environments, though only two—Oxford Dictionaries and the Virtual Reality Society—specify that these images be three-dimensional. Another component of virtual reality emphasized in all three definitions is its interactive nature, allowing users to explore a virtual environment and/or manipulate objects in a virtual space. The Merriam-Webster definition also touches on another aspect of VR: it is designed to stimulate the user's senses, primarily vision and hearing, but occasionally touch as well. Along these lines, another characteristic of VR is its ability to make the users feel as though they have been transported to another place, a phenomenon also known as a "sense of presence."[6] Through its immersive elements that engage the user's senses, virtual reality content can create a convincing illusion that the user is in a virtual space, apart from the one they are inhabiting in the physical world.

Based on these definitions, virtual reality can be characterized as technological system that uses interdependent hardware and software to place users in a computer-generated, three-dimensional environment that is immersive and interactive. Though these are all basic features of VR systems, these traits can manifest themselves in different ways according to how developers designed the system and its content, as well as how users are able to interact with the hardware and software. For example, some content currently being developed has been labeled and

[5] "What is Virtual Reality?" *Virtual Reality Society*. https://www.vrs.org.uk/virtual-reality/what-is-virtual-reality.html
[6] Ibid.

advertised as being "virtual reality," even though it is not fully interactive and its imagery may not even be computer-generated. Both computer-generated images, which are purposefully constructed through the use of software, as well as images recorded or photographed in the real world can be experienced in virtual reality systems, and some VR content even utilizes both CGI and traditional cinematographic elements simultaneously. Even though less interactive and non-CGI content, such as 360-degree video, does not fit into traditional definitions of virtual reality, it has been popularly categorized to fall under that terminology, and should also been considered as virtual reality content for historical, cultural, and preservation purposes.

With all of the different definitions for and the various aspects of virtual reality systems and content in mind, I have found it more helpful to, rather than define virtual reality in a very rigid way, consider VR as existing on a spectrum. In order to clarify what virtual reality is and how it differs from other computer-generated content, as well as to visualize the array of different types of existing virtual reality content, I am going to talk about classifying virtual reality along two different spectrums: a reality-virtuality continuum and a spectrum of interactivity and immersiveness.

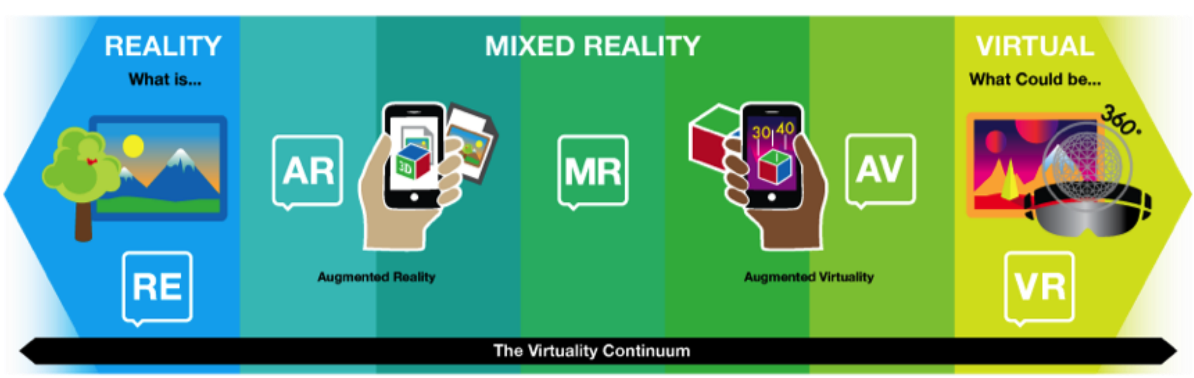

Figure 1.1 The Reality-Virtuality Continuum
(LATIS Labs - https://labs.dash.umn.edu/etc-lab/the-virtuality-continuum-for-dummies/)

Figure 1.1 depicts the Reality-Virtuality Continuum, which ranges from Reality (a completely real world environment) to Virtual Reality (a completely simulated environment). It is a scale of “What is” to “What could be.” This continuum model was first theorized by Paul Milgram in 1994 and it provides a conceptual framework for distinguishing between different types of technology-mediated, graphical experiences.[7]

In addition to “Virtual Reality,” terms such as “Augmented Reality” and “Mixed Reality” have been prominently featured in advertisements for new technological devices. All of these terms address related, but distinct technologies, and Milgram’s continuum is a way of differentiating and understanding them.

Starting on the left end of the continuum, “Reality” refers to, “any environment consisting solely of real objects,” viewed either directly in the real-world or through another display (such as a television, video monitor, or computer monitor) that only shows real-world scenes.[8] It should be noted that merely viewing a real environment through digital means does not inherently make it virtual.[9] The word “virtual” indicates a simulated environment that does not exist in the real world. Digital technology such as computers, tablets, and smartphones can be used to display both virtual/simulated and photographed/real-world content. For example, watching a documentary on a laptop or using Google Street View on an iPhone is not virtual reality.

In the middle of the spectrum lies “Mixed Reality,” which is an umbrella term that

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[7] Paul Milgram, et al. "Augmented Reality: A Class of Displays of the Reality-Virtuality Continuum," *Proc. SPIE Vol. 2351, Telemanipulator and Telepresence Technologies*, 1994.
[8] Ibid.
[9] Khullani M. Adbullahi. “The Reality-Virtuality Continuum: Understanding Augmented and Virtual Reality for Marketing” *Medium*. Apr. 10, 2016. Accessed April 8, 2017. https://medium.com/technology-and-you/the-reality-virtuality-continuum-db166a704c01

includes any medium that incorporates both real and virtual imagery simultaneously. Within Mixed reality, the scale can be further broken down into two sub-categories: "Augmented Reality" and "Augmented Virtuality." Augmented reality, or AR, refers to instances where computer-generated images are seen overlaid on top of real environments, similar to a hologram. Augmented reality can be viewed on computers and phones, such as the popular cell phone game *Pokémon Go*, which shows animated characters superimposed over the real world, using the phone's camera to show the physical environment in real time. Like virtual reality, augmented reality content can also be viewed through a headset display. However, unlike VR, AR headsets do not entirely separate the user from the real world. Instead, augmented reality headsets are see-through, enabling computer-generated images to be projected onto a transparent screen, through which the user retains the ability to see the physical environment around them. Examples of AR headsets include Google Glass and the Microsoft Hololens. While augmented reality refers to virtual imagery superimposed over the real world, augmented virtuality refers to the opposite of that. Augmented virtuality is "…a term currently not in use, but descriptive of technologies on the horizon."[10] Though this technology has seen limited practical application thus far, an Augmented virtuality headset would theoretically situate the user in a primarily virtual space and provide a window through which real objects could also be viewed.

Finally, on the far-right end of Milgram's continuum is "Virtual Reality." Milgram describes VR as "…environments consisting solely of virtual objects, examples of which would include conventional computer graphic simulations, either monitor-based or immersive."[11] Given that Milgram theorized this model in 1994, over two decades before the emergence of today's

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[10] Ibid.
[11] Milgram, et al.

contemporary virtual reality devices, this definition is a bit limited in terms of how the technology is conceived of today. As Khullani M. Abdullahi writes, "This definition is cumbersome and outdated because virtual reality environments can now be launched through a variety of hardware technologies." Abdullahi then proposes a more modern definition: "Virtual reality consists of any environment that is entirely virtual and immersive such that the cognitively transported person interacts with only virtual objects."[12] Abdullahi's definition is broader and encompasses the various means that virtual reality content can be accessed today, and does not limit VR to referring solely to computer-generated content. This definition is helpful when considering the various types of content that are currently designated as "Virtual Reality." These VR experiences can be arranged on a Spectrum of Virtual Reality Content. The following spectrum of VR experiences depicted in Figure 1.2 would rest solely in the "Virtual Reality" end of Milgram's Reality-Virtuality Continuum:

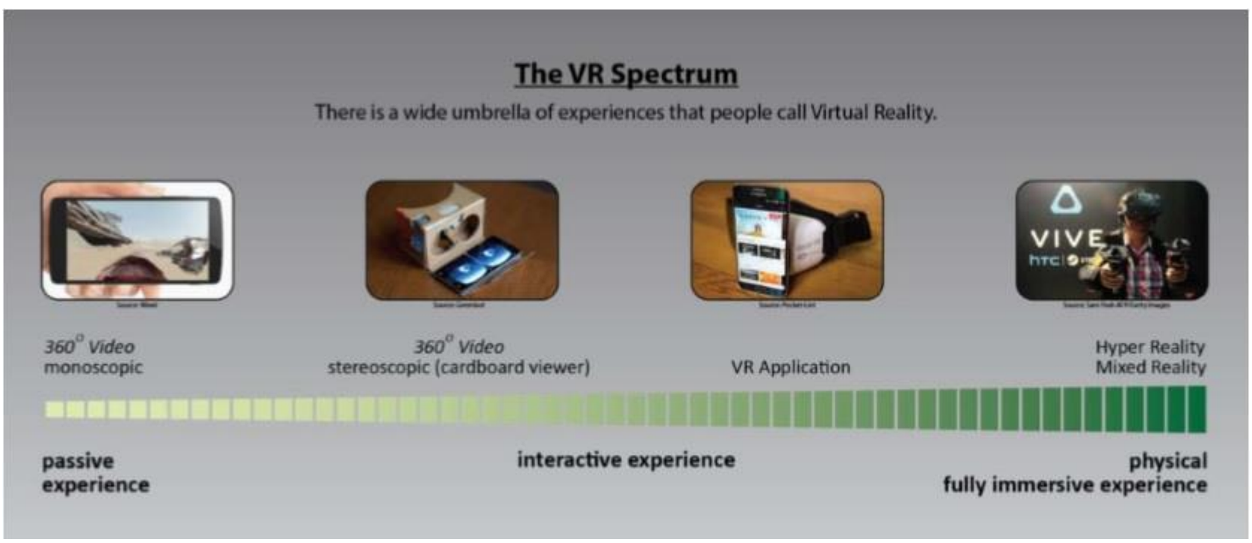

Figure 1.2 A Spectrum of Virtual Reality Content
(Optera Group - http://www.opteragroup.com/ar-vr-glossary-terms/)

[12] Abdullahi

Looking specifically at the virtual reality end of Milgram's continuum, VR technology can also be classified along a spectrum that encompasses a multitude of different types of content and user experiences. The spectrum in Figure 1.2 shows some of these VR experiences arranged by their degree of interactivity and immersiveness. On the left side of the spectrum are monoscopic (two-dimensional) 360-degree videos. This kind of content can be viewed on a cell phone and the video shown is the interior of a spherical or cylindrical image. When the user moves their phone from side to side, their view of the video will shift accordingly. These kinds of videos have, partially for marketing purposes, been referred to as virtual reality. Though they have a place on the VR Spectrum, these monoscopic videos are a passive viewing experience as they offer few interactive elements, and are not particularly immersive as they do not require the use of a headset that would separate the viewer from their real world environment and fill their entire field of vision with the virtual image. In the middle of the spectrum lies more cell phone accessible virtual reality content, which includes three-dimensional, stereoscopic 360 degree videos and other VR applications like cell phone games. These kinds of content are best viewed through a headset display such as a Google Cardboard or Samsung Gear VR, and thus provide some degree immersion as well as interactivity, as the user can move their head to look around the virtual environment, or use buttons on the headset to select items within the VR application. Finally, on the far-right end of the spectrum are fully-fledged virtual reality video games and other fully immersive VR experiences. This includes content accessed through specialized VR headsets such as the Oculus Rift, HTC Vive, and PlayStation VR that are designed specifically for virtual reality content. These devices can also be used with other peripherals such as special gloves and sensors that can detect the user's hand and body movements and map them into the virtual space, thus providing a high degree of immersion and interactivity.

While this spectrum is helpful in understanding some of the different types of technology and content that fall under the category of virtual reality, it is simplified and incomplete. It does not, for example, include content such as 3D models, which can also be viewed in non-VR systems. A more in-depth breakdown of different types of virtual reality content will be provided in chapter 4. This model also does not address the fact that virtual reality hardware systems can also incorporate projection-based systems instead of headsets.

Types of Virtual Reality Systems: HMDs and CAVEs.

Part of what the concept of virtual reality encompasses is the type of hardware used to access the VR content. I will briefly discuss two different modes of virtual reality that utilize hardware in different ways to transport users into virtual spaces: Head-mounted displays (HMDs) and CAVE systems. Both HMDs and CAVEs can be used to create immersive virtual environments that users can interact with. Though I will primarily discuss VR as a headset-based medium throughout this thesis, virtual reality is not bound to one type of hardware technology. Understanding what type of system virtual reality content was created to be viewed in will be important for determining the best preservation plan for the it, as well as contextualizing its original viewing environment for researchers and considering how to provide access to it (i.e. distributing individual headsets or setting up an entire CAVE room for viewing).

Virtual reality is most commonly conceived of in terms of a headset that users wear and through which they see VR content. These devices, such as the Oculus Rift, are called head-mounted displays (HMDs). Some of these devices work by transforming a cell phone into a VR experience, and the more high-end HMDs are stereoscopic headsets designed for more immersive VR experiences. The higher-end HMDs like the Oculus Rift and HTC Vive require powerful PCs to run, or in the case of the PlayStation VR headset, a PlayStation 4 videogame console. An HMD is likely the image that comes to mind when people hear the words "virtual reality."

There is, however, another type of system that can be thought of as a virtual reality experience. A CAVE, which stands for Cave Automatic Virtual Environment, is an enclosed room in which images are projected onto each wall. The name is a reference to Plato's allegory of the cave, a place in which, "…the philosopher discusses inferring reality (ideal forms) from projections (shadows) on the cave wall."[13] Rather than a single user accessing a virtual environment though a head-mounted display, CAVEs allow multiple users at once to experience the virtual space. The images are rear-projected onto each surface of the room, and the users wear 3D glasses to see the three-dimensional effect produced by the projected images. Tracking devices and sensors placed in the room can track the motion of the people in the CAVE and adjust the projected images accordingly, and speakers in the room provide audio effects. Unlike HMDs, CAVE virtual reality systems have not seen consumer adoption and are unlikely to be seen in an arcade or a museum. Rather than being designed for entertainment, CAVEs are more commonly used for scientific research purposes such as visualizing data, and have been implemented primarily in academic research institutions.[14]

CAVEs will have their own unique preservation and conservation challenges that merit further investigation. For this study, however, I will focus primarily on the headset variant of virtual reality. HMDs have seen more widespread adoption among consumers, as well as in the

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[13] Carolina Cruz-Neira, Daniel J. Sandin, and Thomas A. DeFanti. "Surround-Screen Projection-Based Virtual Reality: The Design and Implementation of the CAVE." *SIGGRAPH'93: Proceedings of the 20th Annual Conference on Computer Graphics and Interactive Techniques*. 1993: 135.
[14] Ibid.

entertainment and fine arts sectors. As such, head mounted displays currently have a larger place in the public consciousness, in popular culture, and will more likely find their way into collections within cultural heritage institutions.

The Scope of this Project

For the purposes of this study, I will focus on virtual reality as a system in which the content is most optimally viewed through a head-mounted display. This will include 3D models, 360-degree video, as well as video games and other software content. Each of these areas on their own is a subject for more in-depth research by the preservation community. As little has been written thus far about how to preserve virtual reality collections within cultural heritage institutions, this thesis will provide an overview of the state of virtual reality today, and the array of content types that can fall under the umbrella of "virtual reality." It will consider challenges that collecting institutions may face when dealing with VR collections and propose strategies for preserving virtual reality. By doing so, I hope this project can begin larger and more specific conversations about VR in the archival, preservation, and conservation communities.

Following this introductory chapter, Chapter 2 will provide an overview of the history of virtual reality, and how the medium has seen cycles of boom and bust as projects have been promoted and abandoned over the course of its history. Then, in Chapter 3, I will discuss how virtual reality-related material has thus far been treated in cultural heritage institutions by looking at and comparing the treatment of VR within the collections of two technology museums: The Computer History Museum and Living Computers: Museum and Labs. In Chapter 4, I will describe the different types of content that virtual reality can encompass, and highlight the need to consider different preservation strategies depending on the types of VR content a collecting institution is dealing with. In Chapter 5, I will evaluate existing digital preservation strategies and how they can be applied to virtual reality systems and content. Chapter 5 will also examine other models for preserving complex types of media such as video game preservation and time-based media conservation in order to evaluate how virtual reality preservation plans could potentially borrow practices from them. Finally, in Chapter 6 I will look towards future avenues of research and next steps for preserving virtual reality works, addressing current initiatives underway and identifying work that still needs to be done. In Chapter 6, I will also conclude this thesis by synthesizing and summarizing the material covered in the preceding chapters, discussing challenges collecting institutions may face when dealing with VR and strategies they could explore for its preservation.

Chapter 2: A Brief History of Virtual Reality

Similar to qualifying when the history of motion pictures truly began, it is difficult to pin down an exact date for when virtual reality was first developed. This is in part because virtual reality encompasses an array of technologies, including stereoscopic video, spatialized audio, computer graphics, and various input devices, such as head-mounted displays and haptic gloves, that aid the user in interacting with the virtual world. Though each of these components has their own precursors and histories, they should be considered in conjunction when thinking about virtual reality. The underlying philosophy of VR, placing a user in a fully immersive and interactive virtual environment, should also be considered when examining the medium's history.

Like with motion picture films, virtual reality has many pre-cursors, as well as many early pioneers that contributed to various aspects of its development. One example of an early pre-cursor to virtual reality are Victorian stereoscopes. Stereoscopes were a handheld device reminiscent to a pair of opera glasses that allowed users to see a three-dimensional representation of a two-dimensional picture or drawing. They use lenses to create the illusion of a three-dimensionality from two side-by-side two-dimensional images, in the same way that glasses for 3D movies work, and also how virtual reality headsets work. Of course, stereoscopes were used to view static pictures rather than moving images. Over the centuries since the Victorian era, other devices have been developed to view moving images through headset displays, first utilizing traditional film and video recordings, and later computer graphics.

Based on the definitions of virtual reality outlined in Chapter 1, I will examine virtual reality as an immersive, three-dimensional, computer-generated space that a user can access via a head mounted display. Virtual reality technology in this sense first emerges in the mid-1960s through Ivan Sutherland's pioneering work. From there, virtual reality spent several decades in development out of the public eye, primarily in the research laboratories of NASA and the United States military. By the late 1980s and early 1990s, virtual reality had entered the public consciousness, as the industry touted VR and its many potential applications as revolutionary for science, entertainment, art, and business. By the mid-1990s, however, the virtual reality industry had largely collapsed and had again faded from public view. In the last few years, however, virtual reality has re-emerged and has become a prominent force in the news and in the consumer market, as devices such as the Oculus Rift, HTC Vive, Samsung Gear VR, and PlayStation VR saw public releases in 2015 and 2016. Now, there has been much speculation about whether or not virtual reality is finally here to stay. By considering virtual reality's past, its future and preservation can be critically considered.

Precursors to Virtual Reality: Experience Theaters and Surveillance Devices (1950s-1962)

Virtual reality's most immediate precursors emerged in the 1950s, not from the computer science field, but from the entertainment industry. Morton Helig was a cinematographer who wanted to expand the capabilities of large-screen film formats such as Cinerama and Cinemascope to more completely immerse the viewer in a motion picture. He wanted to create a fully three-dimensional image that filled the spectator's entire field of vision and immersed them in stereophonic audio. He took this idea even further, seeking to incorporate all of the human senses, like smell and touch, and include all of these stimuli in his theorized "Experience Theater."[15] Helig presented his ideas to others in the industry, but none were interested in investing in it. Helig nonetheless proceeded to build a prototype of his idea with the hope that

[15] Grigore Burdea and Philippe Coiffet. *Virtual Reality Technology*. (New York: Wiley, 1994) 6.

investors would be more interested after seeing a functional model.

In the 1950s, Helig worked on a design for the Sensorama Simulator, which was a boxy one-person theater, and patented it in 1962.[16] The Sensorama featured 3D moving images (which were created by the 35mm film projector housed inside), stereo sound, aromas that were dispersed near the viewer's nose at specific points during the film, as well as wind effects generated from a fan, and a seat that vibrated.[17] Helig even produced five different films for the Sensorama, each with their own, specifically designed immersive effects.

According to Scott Fisher in "Viewpoint Dependent Imaging: An Interactive Stereoscopic Display,":

> An environmental simulator, the Sensorama display was one of the first steps toward duplicating the viewer's act of confronting a real scene. The user is totally immersed in an information booth designed to imitate the mode of exploration while the scene is imaged simultaneously through several senses. The next step is to allow the viewer to control his own path through available information to create a highly personalized interaction capability bordering on the threshold of virtual exploration.[18]

Though the Sensorama offered a passive viewing experience of motion pictures, its immersive aspects are a precursor to virtual reality devices. Here, the user experiences the film through a booth-like device, and the aim of the Sensorama is to engage all of the viewer's senses and provide an immersive experience. However, the Sensorama differs from virtual reality in other respects: it provides a passive viewing experience, rather than an interactive one, because there is a lack of user mobility, and by extension, motion tracking. The viewer is stuck in one position inside of the box-like apparatus and cannot look around within the virtual environment.

The Sensorama never took off as Helig wanted it to, as the handful of prototypes he made

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[16] Burdea and Coiffet, 5
[17] Burdea and Coiffet, 7
[18] Scott Fisher, "Viewpoint Dependent Imaging: A Stereoscopic Display" (PhD diss., Massachusetts Institute of Technology, 1981).

failed to entice investors. Even so, Helig's experiments paved the way for virtual reality's development. Following his work on the Sensorama, Helig considered ways of making his device more compact and creating a type of head-mounted television. He designed a headset called the Telesphere Mask[19] that utilized slides and had the ability to immerse the viewer using, "…wide peripheral effects, focusing controls and optics, stereophonic sound, and the capability to include smell."[20] Like the Sensorama, Helig's idea for a television one could wear on their head was meant to fully engage all of the user's senses. And similar to the Sensorama, no investors were interested in this idea either. Though the Telesphere Mask never left the prototype phase, it serves as the first example of a head-mounted display, and helped pave the way for the development of HMDs for virtual reality.

At this time, other headset devices were being developed outside of the entertainment sector for surveillance and security purposes. In 1961, engineers at the Philco Corporation developed the first HMD called the Headsight. The Headsight had a CRT video screen for each eye and utilized a motion tracking system. The device was hooked up to a closed-circuit camera, and was intended for use as a military surveillance tool to remotely assess potentially dangerous situations. The set-up for the system placed the camera in one room and the user in another, separate location. The user could remotely control the camera. By moving their head side to side while wearing the Headsight, the camera would move correspondingly, thus allowing the user to survey the environment.[21] Another similar project occurring in the early 1960s was at Bell Helicopter Company, where another camera-controlled head-mounted display was being

[19] "History of Virtual Reality," Accessed January 15, 2017. https://www.vrs.org.uk/virtual-reality/history.html.
[20] Burdea and Coiffet, 7
[21] "History of Virtual Reality"

developed. This system worked with an infrared camera mounted under a helicopter and was meant to aid pilots in landing at night time.[22] These devices were meant to be used in real-time to monitor situations in the real world, rather than to transport users to virtual spaces, and they worked with video camera systems rather than computer systems. Though the Headsight and Bell Helicopter HMDs lacked computer integration and graphics, they represent steps forward in head-mounted video display technology and paved the way for virtual reality headsets.

An "Ultimate Display": Ivan Sutherland and the First Virtual Reality Headset (1960s)

Virtual reality as a headset-based system through which users experience a computer-generated environment first truly emerged through the work of computer scientist Ivan Sutherland. He was inspired by a visit to the Bell Helicopter Company, where he saw their stereoscopic head-mounted display attached to an infrared camera that was mounted below a helicopter to aid in difficult night landings, leading him to consider the possibilities of virtual reality. He considered using computer-generated graphics, rather than closed-circuit video, to create simulated worlds that users could view through head-mounted displays.[23]

In 1965, Sutherland, now known as "the father of computer graphics," began theorizing about a computer that could display a synthetic world and immerse a user in it. He referred to such a device as "the ultimate display." Sutherland thought that such a display device connected to a powerful computer would provide, "…a chance to gain familiarity with concepts not

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[22] Michael Haller, et al. *Emerging Technologies of Augmented Reality: Interfaces and Design*. (Hershey, Idea Group Publishing, 2007) 44.
[23] Steve Aukstakalnis. *Practical Augmented Reality: A Guide to the Technologies, Applications, and Human Factors for VR and AR.* Addison-Wesley Professional, 2016: 9.

realizable in the physical world. It is a looking glass into a mathematical wonderland."[24] To navigate this wonderland, Sutherland suggested the use of a joystick for the user to control their movements through the virtual space, but he also thought that computers could eventually track a user's body positioning and eye movements and that the virtual environment could be manipulated through the user's physical movements beyond hand motion.[25]

By 1968, Sutherland, along with his student assistant Bob Sproull, had broken ground toward creating an "ultimate display." Working out of Harvard University, where Sutherland was teaching at the time, they developed the first virtual reality device, known as the "Sword of Damocles". Though it was a rudimentary and preliminary iteration of the device he had theorized, the Sword of Damocles presented a simple stereoscopic display of a three-dimensional, computer-generated space. The user accessed this space through a head-mounted display that tracked their head and eye movements and used this sensory input to help the user navigate in the virtual environment.[26] The weight of the CRT monitors in this head-mounted display was so great that the Sword of Damocles had to be suspended from the ceiling for a user to wear it comfortably, and the armature that attached the device to the ceiling also aided in tracking the user's motion.[27] This feature of the device was how it received its name. "The Sword of Damocles" comes from a Greek myth where a man named Damocles ingratiates himself to the deity Dionysius, by lauding his wealth, power, and authority. Dionysius offers to switch places with Damocles, a proposition that is accepted. Sitting on the throne, Damocles is

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[24] Ivan E. Sutherland. "The Ultimate Display." *Proceedings of IFIP 65*, Vol. 2, 1965: 506. http://worrydream.com/refs/Sutherland%20-%20The%20Ultimate%20Display.pdf
[25] Sutherland 507-508.
[26] "The Sword of Damocles and the Birth of Virtual Reality," *Simpublica Magazine*, 19 Mar. 2014. http://www.simpublica.com/blog/2014/03/19/the-sword-of-damocles-and-the-birth-of-virtual-reality/
[27] Burdea and Coiffet, 7

surrounded by luxury and splendor, but above the throne Dionysus placed a large sword hanging by a single horse hair, with the moral being that power and fortune also come with danger and threats.[28] Thus, the weight and burden of Sutherland's head-mounted display on the user led to this nickname.

The visual effects that the Sword of Damocles device provided were simple wireframe geometric figures overlaid on top of the user's view of the real world, similar to what is today referred to as augmented reality. The Sword of Damocles was thus the first HMD that displayed computer-generated graphics, rather than a video or film image.[29] The mechanical arm that attached the HMD to the ceiling also tracked the movement of the user's head, and the view of the wireframe graphics would change according to how the user was positioned.[30]

Though unwieldy in terms of its physical properties and primitive in terms of its computing capabilities, the Sword of Damocles represents the first attempt at a virtual reality HMD as it is conceived of today, and has paved the way for the future of virtual reality and the consumer VR devices currently on the market.

Research Continues: VR Experiments at NASA and the U.S. Military (1970s-1980s)

Even before Sutherland's breakthrough experiments, NASA and the United States military had recognized the potential of virtual reality for use as a training tool. Though more basic aircraft simulations had been used prior to this time period, the 1970s and 1980s saw Sutherland's virtual reality technology being adapted for use as a flight simulator. Sutherland

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[28] Evan Andrews, "What was the Sword of Damocles?" *History.com*, 07 Mar. 2016. http://www.history.com/news/ask-history/what-was-the-sword-of-damocles
[29] "History of Virtual Reality"
[30] Burdea and Coiffet, 9

himself went on to co-found the Evans and Sutherland Military Computer Corporation in 1968, which worked with NASA's Ames Research Center to further develop flight simulators that incorporated interactive virtual reality elements.

Meanwhile, engineer Thomas Furness began developing a virtual reality flight simulator for the Air Force. Working out of the Wright Patterson Air Force Base from 1966 to 1989, Furness developed virtual reality technology to expand the functionality of previous military flight simulators and solve problems related to their operation. This included simulating, "the complexity of having many complicated computers but one operator, seeing at night, aiming the airplane and systems, and having adequate awareness and view of both the inside and the outside of the airplane."[31] Furness also developed several new head-mounted displays in which he implemented these features. One of his projects, called the "Super Cockpit," was a wearable facsimile of a fighter jet cockpit that prompted pilots to perform demanding flying maneuvers and tasks via a three-dimensional audiovisual display that also incorporated haptic touch-sensitive elements.[32] Using virtual reality as a tool for training pilots and astronauts thus became the technology's first practical application.[33]

Throughout this period of virtual reality's development in the 1970s and 1980s, the technology was largely kept out of the public eye. The hardware and software used in these

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[31] Erin Carson. "Where VR Should Go from Here, according to 'the Grandfather of VR'." *Techrepublic.com*, June 10, 2015. Accessed January 10, 2017. http://www.techrepublic.com/article/where-vr-should-go-from-here-according-to-the-grandfather-of-vr/.

[32] "Virtual Reality Pioneer Dr. Tom Furness Joins Envelop VR as Its Senior Scientific Advisor" *Business Wire*, July 14, 2015. Accessed March 12, 2017. http://www.businesswire.com/news/home/20150714006173/en/Virtual-Reality-Pioneer-Dr.-Tom-Furness-Joins.

[33] Adi Robinson and Michael Zelenko, "Voices From a Virtual Past: An Oral History of a Technology Whose Time Has Come Again," *The Verge*. Accessed November 29, 2016. http://www.theverge.com/a/virtual-reality/oral_history

systems were expensive to create and develop, and VR was thus limited to scientific research and military purposes during this era of its history.

VPL Research: Broadening the "Goggles and Gloves" User Base (1985-1990)

Significant developments in terms of broadening the applications for virtual reality beyond scientific and military use came with the establishment of the company VPL Research in 1985. The founder of VPL, Jaron Lanier, is often credited with either coining or popularizing the term "virtual reality." VPL (which stands for Visual Programming Language) developed several pieces of hardware and software that helped virtual reality research proliferate in the 1980s and 1990s.

VPL's head-mounted display called the EyePhone, as well as their input device called the Data Glove and the full-body Data Suit facilitated virtual reality research. These devices were available individually, but could also be purchased together as a kit along with a specialized computer and software developed by VPL. With this complete virtual reality system available as a package, developing VR technology became more feasible for research institutions and universities. According to Howard Rheingold's seminal book on the history of early virtual reality, "VPL was the 'goggles and gloves' vendor to the research world—the first vendor of 'off-the-shelf' VR systems. Laboratories no longer needed to reinvent the virtual wheel and build their own HMDs and input devices."[34]

VPL Research advertised their virtual reality hardware and software for a wide range of different applications and business sectors.

[34] Howard Rheingold. *Virtual Reality*. Summit Books, 1991: 165.

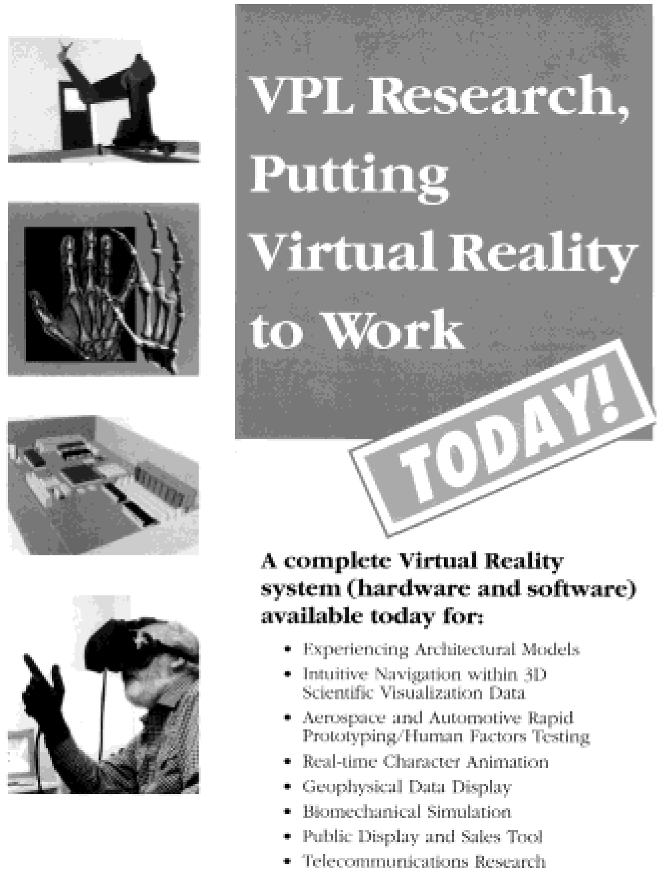

Figure 2.1: Promotional Material from VPL Research
(http://www.sgistuff.net/hardware/systems/documents/vpl1.jpg)

As seen in the advertisement above, VPL Research promoted their virtual reality hardware and software for use in many different fields. This included using VR to view three-dimensional architectural models, looking at scientific data in new ways, animating character models, as well as for other scientific and telecommunications research purposes. From Ivan Sutherland's Sword of Damocles to VR flight simulators to VPL's EyePhone system, this history demonstrates that virtual reality was not always seen as merely an entertainment medium, but one that could be used by businessmen, scientific researchers, and artists to help shape their work.

By selling their devices in complete kits to virtual reality researchers in a multitude of different sectors, VPL made the devices more accessible to those who wanted to further develop the technology. As these devices were too expensive for most purposes, they saw more adoption in research labs than on the consumer market. On its own, an EyePhone Model 1 cost $9,400 in 1991,[35] and a complete VPL virtual reality system including the peripheral devices and a computer to run the programs could cost upwards of $250,000.[36] Despite their high price point and limited adoption, however, the EyePhone, Data Glove, and Data Suit promoted and propagated virtual reality research, and raised public awareness about virtual reality.

The Rising Popularity of Virtual Reality (1980s-1990s)

While virtual reality technology was largely kept out of the public eye during the first few decades of its history, this began to change in the late 1980s as the technology became more accessible to researchers and developers. Following the emergence of off-the-shelf virtual reality kits by VPL Research and other developers, news of this emerging technology began to permeate the public consciousness. As depicted in the VPL Research advertisement in Figure 2.1, virtual reality was promoted as a game-changing technology for a large number of business sectors. It was also seeing increasing use in the arts and humanities. Artists began creating VR-works, and VR became a prominent theme in the literature, movies, and overall popular culture of the time.

In the early 1990s, virtual reality became a new medium for artists to work in and VR artworks were showcased in prominent museum exhibitions. In 1993, the Guggenheim Museum

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[35] "VRWiki - VPL EyePhone." Accessed March 1, 2017. https://vrwiki.wikispaces.com/VPL+EyePhone#VPL EyePhone HRX.
[36] Paul Sorene. "Jaron Lanier's EyePhone: Head and Glove Virtual Reality in the 1980s." *Flashbak*. November 24, 2014. Accessed March 1, 2017. http://flashbak.com/jaron-laniers-eyephone-head-and-glove-virtual-reality-in-the-1980s-26180/.

presented an exhibition entitled *Virtual Reality: An Emerging Medium*, which featured VR works by prominent media artists such as Jenny Holzer and Thomas Dolby.[37] Another prominent artist working with virtual reality was Char Davies. With her immersive works *Osmose* (1995) and *Ephémère* (1998), Davies created virtual environments for museum goers to experience. With Davies's works, users could don a VR headset and vest filled with motion sensors to navigate computer-generated nature scenes, with the vest tracking slight changes in balance and breathing to create a feeling of the user floating ghost-like through the scenery.[38]

Virtual reality had also begun to permeate the popular culture of the 1980s and 1990s. Novels, such as William Gibson's *Neuromancer* (1984) and Neal Stephenson's *Snow Crash* (1992) offered readers a glimpse of this very real emerging technology through science fiction scenarios and popularized the cyberpunk aesthetic. This period also saw a number of movies being made surrounding themes of apprehension over computers, technology, and humanity's relationship to them. This includes films such as *Tron* (1982), *The Matrix* (1999), and *Existenz* (1999)—movies that, though not directly about virtual reality, offer related imagery and subject matter. Other movies very prominently featured virtual reality, such as *Johnny Mnemonic* (1995) and *Virtuosity* (1995). The most enduring example is *The Lawnmower Man* (1992), a popular cult film about a scientist who experiments with virtual reality to augment human intelligence. *The Lawnmower Man* also features the VPL EyePhone and DataGlove, and these devices can be seen in many of the scenes throughout the movie. *The Lawnmower Man* spawned a sequel as

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[37] Kim Patterson. "Virtual Reality: An Emerging Medium (1993)." *Virtual Reality in Art*. October 16, 2014. Accessed January 3, 2017. https://kimpattersonvirtualreality2014.wordpress.com/2014/10/16/virtual-reality-an-emerging-medium-1993/

[38] Robert Russet, *Hyperanimation: Digital Images and Virtual Worlds*. John Liberty Publishing, 2009. 172-195.

well as two video game adaptations, and it is currently rumored that it will be remade as a virtual reality experience for today's VR devices. There was even a children's television show called *VR Troopers* that aired from 1994 to 1996. *VR Troopers* was produced by Saban Entertainment, the same company behind *Mighty Morphin Power Rangers*, and it capitalized on the popularity of both *Power Rangers* and virtual reality.

With expanded coverage of real-world virtual reality technological developments in the media and the showcasing of virtual reality artworks in museum exhibitions, coupled with the rising prominence of VR in popular novels, movies, and television shows, public anticipation for the day virtual reality devices would reach consumer markets grew exponentially throughout the early 1990s.

The First Wave of Consumer VR (1987-1995)

One of the most popular uses for virtual reality today is using it as way to experience video games. VR game development began in the late 1980s and there was much anticipation for consumer-friendly, affordable virtual reality gaming systems. In 1987, a virtual reality gaming device hit the consumer market: Sega's Segascope 3D, a rudimentary 3D headset that could be used with several games on Sega's Master System. In 1989, the Power Glove, a much more affordable derivative of VPL's Data Glove, was released as an accessory for the Nintendo Entertainment System and could be used to play select games on the popular video game console. Though peripheral devices like the Segascope 3D and the Power Glove did not offer a complete virtual reality experience, they were early consumer products that allowed for more interactive video games, and offered users a glimpse at the potential for more immersive virtual reality experiences in the future.

The early 1990s also saw the development of virtual reality arcade machines developed by Virtuality, some of which could support multiple players at once. The game libraries for these devices were fairly minimal were largely comprised of shooting games and flight simulators. Though the initial reception of these devices was positive and hopes were high for future VR products, virtual reality soon began losing its momentum as a consumer product.

Sega announced the Sega VR for their Genesis console in 1993, expecting to release it early in 1994. The product was extensively marketed and prototypes were shown at electronics shows. Anticipation for its release was high. In *Virtual Reality Technology*, which was first published in the early 1990s, the authors predict the successful release of the Sega VR, lauding it as the "first immersive VR home-based video game" and calling it "…no less than a quantum leap forward for the VR industry."[39] Unfortunately, the Sega VR was never released and never became the spark that ignited the consumer virtual reality craze, as predicted. The project languished in development and its release date was delayed several times before Sega ultimately cancelled it entirely. Atari had plans for a similar virtual reality device for their Jaguar console, but it too was cancelled in 1995.

The only comparable VR gaming device released at this time was Nintendo's Virtual Boy console. Although the Virtual Boy had a 3D stereoscopic display, it lacked immersive graphics and did not offer a true virtual reality gaming experience. The visual interface only displayed two colors: red and black. This was far from the immersive computer graphics consumers were anticipating. The device was also cumbersome to use and heavy, and there were many reports of the Virtual Boy inducing nausea and headaches. When it was released in 1995, the system also retailed for $179.95, which many considered too steep a cost for the limited VR gaming

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[39] Burdea and Coiffet, 13

capabilities of the device.[40] The device's disappointing graphical capabilities coupled with the reports of nausea and other ailments users experienced, as well as the high price point of the Virtual Boy led to it receiving much criticism and selling very poorly.

Following the failure of the Virtual Boy and the disappointing cancellations of VR headsets from Sega and Atari, interest in virtual reality gaming declined.[41] The market for virtual reality gaming stagnated until recently, beginning in the mid-2010s, where it has experienced a resurgence of interest due to devices like the Oculus Rift and the Samsung Gear VR, which offer much more immersive VR experiences and are more lightweight and user-friendly than their predecessors from the 1980s and 1990s.

The Rise and Fall and Rise of Virtual Reality

Following the cancellations of many anticipated VR products and the poor sales of the Nintendo Virtual Boy, the hype surrounding virtual reality had largely fizzled out by the mid to late 1990s. Many of the companies developing virtual reality hardware and software, including VPL Research, went bankrupt and were dissolved. In the period between the late 1990s and the 2010s, virtual reality had mostly receded from the public consciousness, and again returned to the more private research world where a few VR-related experiments persisted at university laboratories.

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[40] Benj Edwards. "Unraveling the Enigma of Nintendo's Virtual Boy 20 Years Later," *Fastcompany.com*, August 21, 2015. Accessed March 3, 2017. https://www.fastcompany.com/3050016/unraveling-the-enigma-of-nintendos-virtual-boy-20-years-later

[41] K. Thor Jensen. "The History of Virtual Reality Video Games," *Geek.com*, April 15, 2016. Accessed January 15, 2017. http://www.geek.com/news/the-history-of-virtual-reality-games-1652225/

Figure 2.2: Virtual Reality's Rise and Fall in the 1990s
(Visualized Through Google Books N-Gram Viewer)

The graph above shows the sharp rise of mentions of the phrase "virtual reality" in the early 1990s and their gradual decrease throughout the decade. To illustrate this trend, I searched for the term "virtual reality" in Google Books's N-gram Viewer, which scans books for the number instances the chosen search term appears in them. Unfortunately, N-gram Viewer only charts this trend up until the year 2008 (when interest in virtual reality was still at a low point, and VR was not being discussed much). If the chart were to continue several more years, there would likely be another huge spike in the instances of the words "virtual reality" beginning in the 2010s and continuing to the present day, as there has been a resurgence of interest in virtual reality.

Virtual Reality Today (2010-2017)

Beginning in the early 2010s, a renewed interest in virtual reality has been growing. Momentum has been building around the VR devices currently on the market—including the Oculus Rift, HTC Vive, Samsung Gear VR, PlayStation VR, and Google's Cardboard and Daydream View headsets—and a large and growing amount of VR content for a wide array of different applications is being developed for them.

In 2010, inventor Palmer Luckey developed a new prototype for a virtual reality headset and launched a Kickstarter campaign to fund the project. Luckey's device is now known as the Oculus Rift, and though the Kickstarter campaign had a $250,000 goal, there was enough public interest in VR for Luckey to raise $2.4 million in pledges to continue developing his headset.[42] Prototypes of the Oculus Rift were shown at the E3 video game conference in 2012 and 2013, reintroducing virtual reality into the video game industry, where the device was received very positively. Following these successful public demonstrations, Facebook purchased Oculus in 2014 for $2 billion.[43]

Around this time, other prominent companies in the tech industry began investing in virtual reality and developing their own devices. The video game company Valve partnered with HTC to develop a high-end virtual reality headset (which would eventually become the Vive) and Sony began work on an HMD to be used as an accessory with their PlayStation 4 console. With the support from tech industry juggernauts from Facebook to Sony, momentum once again began to build around virtual reality.

While Oculus, HTC, and Sony were developing their high-end virtual reality products, the first of the current wave of VR HMDs were released to the public. The first of these VR headsets was a minimalistic model: the Google Cardboard. The Cardboard, first released in 2014, is a simple cardboard box with stereoscopic lenses inside that transform one's smartphone into a virtual reality viewing device. The Cardboard is compatible with iPhone and Android

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[42] Stuart Dredge. "The Complete Guide to Virtual Reality- Everything You Need to Get Started." *The Guardian*. November 10, 2016. Accessed February 8, 2017. https://www.theguardian.com/technology/2016/nov/10/virtual-reality-guide-headsets-apps-games-vr

[43] Peter Rubin. "The Inside Story of Oculus Rift and How Virtual Reality Became Reality." *Wired*. May 20, 2014. Accessed February 8, 2017. https://www.wired.com/2014/05/oculus-rift-4/

smartphones and Google currently sells the device for fourteen dollars, making it an affordable, highly portable, user-friendly solution to virtual reality. The design for the Cardboard is also open source, so other companies and individuals are free to build their own basic HMD and customize it however they wish. In 2015, *The New York Times* even mailed out Google Cardboards to millions of their newspaper subscribers, offering a large number of people a taste of virtual reality's potential.[44]

Since the Cardboard, several more high-end VR devices for cell phones have been released. In 2015, Samsung released the Gear VR, which is compatible with Samsung smart phones, and in 2016, Google came out with another, fancier headset called the Daydream View, which works with Google Android phones. Both of these devices have expanded the user base for smartphone-based virtual reality. Though they do not provide the most immersive or highest resolution VR experiences, the Gear VR and Daydream View provide more affordable options for users interested in virtual reality.[45]

2016 saw the consumer release for several highly anticipated VR devices: Oculus Rift, HTC Vive, and PlayStation VR. Both the Oculus Rift and the HTC Vive require a powerful PC to function, and provide the most high-end, immersive and interactive VR experiences currently available. The Rift currently retails for $599 and the Vive costs $799, though this does not include the price of the computer needed to use them. The PlayStation VR ($399) is sold as an accessory for the PlayStation 4 and is currently the only video game console-compatible virtual reality headset. Even taking the cost of a PlayStation 4 console into account, however, the

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[44] Tom Simonite. "Google Aims to Make VR Hardware Irrelevant Before It Even Gets Going." *MIT Technology Review.* November 3, 2015. Accessed February 20, 2017. https://www.technologyreview.com/s/542991/google-aims-to-make-vr-hardware-irrelevant-before-it-even-gets-going/

[45] Dredge

PlayStation VR is currently the most affordable of the three higher-end head mounted displays available.[46]

These examples show the wide range of VR devices currently on the market. From the ultra-powerful, high-end models to literally a piece of cardboard, virtual reality is becoming accessible to an increasingly larger user base, and lots of content is being developed for all of these devices.

Just like in the early 1990s, virtual reality is being advertised for a wide array of applications beyond video gaming purposes. This includes being used for medical and therapeutic purposes, from being used to train surgeons to being used to treat patients, such as for physical therapy exercises. As VR has the potential to transport users to remote locations, it is also being used in the tourism industry (such as remotely visiting exotic locales, cultural landmarks, and museums across the globe) as well as for real estate purposes (taking a virtual tour of a property for rent or sale).[47] It is again being used by the research sector, for visualizing data models or viewing three-dimensional architectural models.

Virtual reality is also once again being used as a tool for artists. With VR software applications such as TiltBrush for the HTC Vive and Medium for the Oculus Rift, users can create 3D paintings and sculptures within virtual reality. Prominant artists have taken to the medium as well, and their work is being exhibited in renowned museums such as the Whitney Museum of American Art and the New Museum. The New Museum recently hosted a virtual reality fellow named Rachel Rossin, whose VR-based work has been exhibited there.[48] VR is

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[46] Ibid.

[47] Ibid.

[48] Liz Stinson, "Rachel Rossin's Trippy Paintings of Reality Seen Through VR," *Wired*. November 13, 2015. Accessed March 30, 2016. http://www.wired.com/2015/11/rachel-rossins-trippy-paintings-of-reality-as-seen-through-vr/

also being explored as an "empathy building machine" that enables users to understand others by placing them in their point of view. One collective of artists and researchers called BeAnotherLab has explored this idea in an interactive performance installation called *The Machine to be Another*. This work requires two participants simultaneously: one wears a camera on their head and the other wears a VR headset through which they view the live video feed from said camera. Based out of a studio in Barcelona, *The Machine to be Another* has been installed in galleries, museums, and other art exhibition spaces all over the world.[49]

Virtual reality is also emerging as a prominent force in the motion picture industry, with new VR video works being created and shown at film festivals such as Sundance, Tribeca, and Cannes. Beginning in 2016, the Tribeca Film Festival introduced a separate program devoted to virtual reality works called The Virtual Arcade. VR movies encompass a wide array of genres and subject matter and can be produced through live-action cinematography or computer animation. These cinematic works explore new fantasy worlds and narratives and also are used to create powerful, socially and politically-oriented documentary experiences. Well-known movie directors are also showing interest in the medium, including Kathryn Bigelow, who partnered with National Geographic to co-direct the short VR documentary *The Protectors* (2017), and Alejandro González Iñárittu, whose VR installation *Carne y Arena* (2017) was the first virtual reality experience to be included in a Cannes Film Festival program in 2017. Virtual reality motion pictures are also seeing positive critical reception and award show accolades, perhaps signifying the medium's acceptance as a cinematic form within the industry. In 2016, the Academy of Motion Picture Arts and Sciences even nominated the VR short *Pearl* for an

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[49] "The Machine." *The Machine to Be Another*. Accessed April 15, 2017. http://www.themachinetobeanother.org/?page_id=764

Academy Award in the category of Best Animated Short.

From video games, movies, and art to business, medicine, tourism, scientific research, and cultural scholarship, virtual reality's potential uses are being explored in a wide array of different sectors. Coupled with the ever-growing number of virtual reality headsets being released to consumers, from affordable cell phone-compatible headsets to powerful gaming devices, VR is expanding in terms of accessibility as well. Though this wave of VR is still on its way to becoming a lasting, pervasive feature of the social and technological landscape, the past few years have shown that it is seeing increasing adoption in a large number of different contexts.

A Rift in VR's History

Over the course of its history, virtual reality has taken a number of different forms and has been used for a wide array of purposes. Proto-VR devices from the Victorian stereoscopes to Morton Helig's Sensorama aimed to provide entertainment through optical illusions and immersive cinematic experiences, while video display headsets like the Philco Headsight were a means of conducting surveillance and monitoring potentially hazardous or unsafe real-world environments. With the addition of computer graphics to video headset technology, early virtual reality HMDs from Ivan Sutherland's Sword of Damocles to Thomas Furness's flight simulators emerged, and VR was at first primarily used for military and scientific experiments, such as training pilots and astronauts. From there, virtual reality hardware and software created by VPL Research and other vendors expanded the range of applications for the technology, from visualizing architectural models to revolutionizing medical research and business methodologies. Finally, in the 1990s and again today, virtual reality has predominantly been viewed as a means of consumer entertainment, from video games to other moving image content, as well as being used for artistic purposes. These diverse applications throughout virtual reality's history suggest a plethora of potential uses for the technology, and understanding these uses will be important for creating specialized preservation and conservation plans for historical VR objects, as well as contextualizing them for future researchers. If virtual reality hardware and software are acquired by a cultural heritage institution, an understanding of what that specific VR object was used for will be helpful to researchers who wish to study the piece.

In the 1990s, virtual reality was heavily promoted as the next breakthrough in a wide array of industries as well as in consumer entertainment. At the time, the technology did not see widespread adopted and died down. With the current resurgence of VR in the public consciousness and in consumer markets, hype is again being built around the technology. Given the boom-and-bust cycle that VR experienced previously, there has been much speculation about whether, this time around, virtual reality will be here to stay or if it will again fade away and be viewed as a passing fad.

Understanding the relationship between historical VR and current VR will be important for contextualizing these devices and their content when preserving them. Regardless of whether or not today's virtual reality devices such as the Oculus Rift, HTC Vive, and Samsung Gear VR will see increasing adoption by consumers and content development by artists, filmmakers, and software developers, or again fall by the wayside, now is the time to begin considering how these materials can be preserved and made accessible in the future. By looking at how older virtual reality devices are already being handled in cultural heritage institutions, lessons can potentially be learned for how the current wave of VR technology and content can be effectively preserved.

Chapter 3: Historical VR in Cultural Heritage Institutions

Before considering preservation methodologies for the current wave of virtual reality devices and applications, looking at collections of historical virtual reality systems and examining efforts to archive and preserve them in cultural heritage institutions can illuminate what has already been done, and what further preservation and archival practices should be considered. My aim initially was to locate existing collections of historical virtual reality systems and assess how these collections were being preserved in an attempt to evaluate current practices and inform practices for preserving the current wave of virtual reality. Based on my research, there are currently very few cultural heritage institutions actively collecting virtual reality and virtual reality-related materials.

The first direction of this research was to examine the collections of art museums that I knew had exhibited virtual reality artworks in the 1990s, such as the Guggenheim Museum and the San Francisco Museum of Modern Art, and museums that have a designated time-based media conservation department such as the Museum of Modern Art, to see if any of them were actively collecting and preserving virtual reality artworks. This research trajectory ultimately led to a dead end. The institutions I contacted either informed me that they did not have any VR in their collections, or they never responded to my inquires. I was also unable to locate any records of VR artworks in their online collection catalogs. My next tactic was to contact technology museums to see if they had any virtual reality collections. In this endeavor, I found some success locating historical virtual reality materials.

Ultimately, I was able to find collections of virtual reality at two technology museums: The Computer History Museum in Mountain View, California and Living Computers: Museum and Labs in Seattle, Washington. As case studies for how VR is currently being preserved, I will discuss the VR items within the collections of these two museums, and identify the current practices at each site for preserving historical virtual reality artifacts.

From my search for historical virtual reality collections, it seems that very little of VR's early history remains, as few institutions are actively collecting it. By locating and analyzing collections of VR, I wanted to answer the questions: How have institutions been thus far preserving virtual reality and what exactly are they collecting? What does it mean to preserve virtual reality? Looking at how VR and VR-related materials in the collections of the Computer History Museum and Living Computers: Museum and Labs are cataloged, described, documented, and exhibited will shed light on current practices and how they should be re-evaluated when cultural heritage institutions begin collecting more of yesterday's and today's virtual reality.

Institutional Backgrounds

To contextualize the environments in which these historical VR collections are situated, I will begin by briefly summarizing the mission statements and collecting policies of the Computer History Museum and Living Computers: Museum and Labs.

Working as a nonprofit organization, the Computer History Museum's mission is to, "preserve and present for posterity the artifacts and stories of the information age."[50] The museum claims to have the world's largest collection of computing artifacts, including hardware and software, as well as documentation, still and moving images, oral histories, and other computer-related ephemera. It seeks to preserve a "comprehensive view of computing history,

[50] "Who We Are Overview," *Computerhistory.org*. Accessed February 1, 2017. http://www.computerhistory.org/about/.

one that includes the machines, software, business and competitive environments, personal recollections, and social implications" of the computer.[51] The museum has a strong educational mission and offers programming and events geared toward all levels of learners, from K-12 classes to college and university groups.

The Computer History Museum also has two specialized centers of research: the Exponential Center and the Center for Software History. The Exponential Center seeks to advance entrepreneurship and innovation in the computing industry, exploring the people and companies that develop emerging technologies. Meanwhile, the Center for Software History aims to collect, preserve, interpret, and present the history of software and the individuals who develop it.[52] The Center for Software History's work includes conducting oral histories of computing pioneers and collecting important and historical pieces of source code. To understand how virtual reality technology fits into the context of the Computer History Museum's collections and missions, I interviewed the museum's digital archivist, Andrew Berger, as well as David C. Brock, director of the Center for Software History.

Founded by Microsoft Co-founder Paul Allen and comprised of Allen's personal collection, along with other donated computer artifacts, Living Computers: Museum and Labs strives to "…maintain running computer systems of historical importance."[53] To this end, the museum's engineering team works to restore and refurbish computer systems and keep them running so guests can experience these computing environments in the ways they originally

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[51] "The Collection Overview," *Computerhistory.org*. Accessed February 1, 2017. http://www.computerhistory.org/collections/.
[52] "Centers Overview," *Computerhistory.org*. Accessed February 1, 2017. http://www.computerhistory.org/centers/.
[53] "Living Computers - Computer Renovation." *Livingcomputers.org*. Accessed January 10, 2017. http://www.livingcomputers.org/Discover/At-The-Museum/Computer-Renovation.aspx.

functioned through hands-on exhibitions in the museum. Through these restoration efforts, Living Computers aims to "…ensure authenticity and safeguard against avoidable risk as machines are brought back into service."[54] Many of the exhibits at the museum feature fully functioning historical computing systems that visitors can interact with. This includes all varieties of supercomputers, mainframes, minicomputers, and microcomputers, as well as interactive exhibits involving robotics, virtual and augmented reality, video games, the Internet, and other computer-based technologies. To investigate the virtual reality objects in the Living Computers collection and how they are conserved according to the museum's mission statement, I spoke with their librarian/archivist, Cynde Moya and one of their project managers, Rob Schmuck.

Both the Computer History Museum and Living Computers: Museum and Labs are deeply concerned with the history of computers and providing access to these artifacts to their visitors via their exhibitions. While neither museum is primarily concerned with virtual reality specifically, both include VR devices and related materials in their collections. I will compare and contrast the collections of virtual reality within the two institutions, first examining the specific VR artifacts in these collections. Then, I will assess how these VR collections are described in the online collection catalogs and how they have been exhibited at the two museums.

Two Virtual Reality Collections: A Comparative Analysis

The following chart in Figure 3.1 shows the breakdown of the virtual reality and virtual reality-related materials in the collections of the Computer History Museum and Living

[54] Ibid

Computers: Museum and Labs. The information was found by searching the online collection catalogs of both institutions.[55] I have broken down my findings of virtual reality collection items into four categories: "VR Headsets," "Other VR Hardware" (which includes peripheral input and output devices such as haptic gloves, haptic suits, customized mice, and display monitors), "VR-Related Materials" (non-hardware and non-software objects pertaining to virtual reality, such as photographs, texts, and moving image materials), and "VR Software." The size of these two collections and the breakdown of the materials within them is visualized in the following chart:

Institution	**VR Headsets**	**Other VR Hardware**	**VR-Related Materials**	**VR Software**
Computer History Museum[56]	8	12	36	0
Living Computers: Museum and Labs[57]	23	51	85	0

Figure 3.1: Breakdown of VR Items in the Technology Museum Collections

Both institutions have a number of different models of virtual reality headsets in their collections, as well as many different peripheral input and display devices. For both collections, this includes virtual reality headsets and hardware from the 1980s-1990s era of virtual reality as well as examples of more current models. In terms of VR-related materials, both museums have several books and scholarly journal articles pertaining to virtual reality in their collection.

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[55] The catalog for the Living Computers: Museum and Labs collection can be found at http://opac.libraryworld.com/opac/home.php and the Computer History Museum's online catalog can be found at http://www.computerhistory.org/collections/search/

[56] For the Computer History Museum, these numbers are estimated based on the searches performed. Only two headsets appear when searching "virtual reality". The others were found when searching for "goggles", "sword of damocles", "virtual", and "sega".

[57] For Living Computers: Museum and Labs, searching only for "virtual reality" yielded all found search results.

However, I found that both of these collections of VR-related materials did not include any user manuals for operating or maintaining any of the VR headsets or accessories. The examination of these collections also revealed that neither institution currently has any virtual reality software or other types of content that could be viewed on any of the VR headsets. When I asked Andrew Berger if the Computer History Museum had any VR software, he responded that the institution has only recently started to process their software collection, and has not, "…worked on preserving virtual reality artifacts as software objects, rather than physical objects."[58] He confirmed that, to his knowledge, the museum had both literature and audiovisual material about virtual reality (the "VR-Related Materials" column in Figure 3.1), and did not have any VR software itself.[59] Similarly, Cynde Moya at Living Computers: Museum and Labs also confirmed that the museum did not currently have any VR software in its collection.[60]

While software is within the collecting policies of both institutions, neither has acquired any virtual reality software. Both the Computer History Museum and Living Computers: Museum and Labs rely primarily on donations to receive the majority of the items in their collections. It appears that in instances where virtual reality and virtual reality-related materials have been donated to these institutions, software was not included in the donations. However, the archivists at both institutions expressed interest in acquiring virtual reality software when I spoke with them. As Living Computers has the goal of providing visitors access to restored computers to allow them to experience software on original hardware, it follows that they would welcome a donation of historical VR software along with a headset. David C. Brock at the Computer

[58] Andrew Berger. "Re: Questions about conservation and virtual reality." Message to Savannah Campbell. December 9, 2016. E-mail.
[59] Ibid.
[60] Cynde Moya. Personal interview by Savannah Campbell. January 10, 2017.

History Museum's Center for Software History stated that, in an ideal scenario, they would like to receive in a donation of a virtual reality system the following items: the headset, the computer, the software, and the input/output peripherals, all in working order. The museum would then proceed to create a disk image of the computer's hard drive and catalog all of the items as a lot (catalog the items individually and the relationships between them), catalog the hard drive image and put technical information about it alongside all the other descriptive metadata.[61] Although Brock's scenario is a hypothetical one, it serves as a good model for how institutions could accession and begin to preserve a virtual reality system.

As of yet, I have not yet been able to locate any historical VR software within any cultural heritage institution's collection. This being the case, I am currently uncertain how much, if any, of the content and software applications for early virtual reality systems still survives.

Beyond solely looking at the number of items in these two collections, I will also examine and evaluate how these institutions catalog VR items and what kinds of metadata they use. By doing so, I will to discuss the kinds of metadata that should be included in records to both aid researchers in locating VR items within the collection and aid preservationists in managing and understanding the materials within a VR collection and how they should be cared for.

Metadata and Discoverability

When searching for virtual reality collections within the online catalogs for the Computer History Museum and Living Computers: Museum and Labs collections, the metadata contained in the catalog records greatly impacted my ability to find virtual reality devices and materials.

[61] David C. Brock. Personal interview by Savannah Campbell. February 13, 2017.

Discoverability was an issue when searching the Computer History Museum's collection. Many of the VR artifacts in the collection are not accurately described, with some items being either mislabeled or missing key descriptive information. This made the exact number of VR-items they have difficult to discern. When performing a search for "virtual reality" in the catalog, only two headset devices came up: an ANTVR headset[62] titled "virtual reality goggles" and a second-generation Oculus Rift development kit, which at least was named "Oculus Rift DK2". Immediately, I knew this did not reflect the entirety of the Computer History Museum's virtual reality HMD collection, as I had previously learned through my research on the history of VR that Ivan Sutherland's original Sword of Damocles headset, significant as being one of the very first incarnations of virtual reality as it is conceived of today, had been acquired by the museum. Through a conversation with the museum's digital archivist Andrew Berger, I confirmed that the Computer History Museum had the Sword of Damocles in its collection.[63] When I performed a search for "sword of damocles" in the online catalog, the correct catalog entry for the device appeared, though nowhere in its description did it include the words "virtual reality". Instead, the entry for the Sword of Damocles has the keywords "Output; Sword; Damocles; Monitor; Video." Not only would a researcher looking for historical VR therefore have a difficult time locating this significant device, someone who happened to come across the entry for the Sword of Damocles would not have a full understanding of what the device actually is.

Following my search for the Sword of Damocles, I tried several other search terms to find other VR devices that may had also been cataloged under different keywords. A search for

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[62] The ANTVR headset is a cell phone-compatible HMD that was released in December, 2014 and was sold with Lenovo smartphones as part of a kit, though none of this date and brand information was include in the Computer History Museum's catalog record for the item.

[63] Berger

“goggles” yielded three more devices, two of which were titled “goggle assembly” When looking at the pictures in the two entries for “goggle assembly”, these devices prominently display the VPL Industries logo and are very likely models of the EyePhone. The third device that was searchable by “goggles” was a set of Vectrex Arcade System 3-D goggles, an early example of consumer goggles to enhance video game experiences. Following this systematic search strategy, a search for “virtual” showed that the Computer History Museum had a Nintendo Virtual Boy in their collection and a search for “Sega” yielded an entry for SegaScope 3D Glasses for the Sega Master System. As with the Sword of Damocles, the keywords for the SegaScope 3D Glasses are listed as “Output; Display; Monitor; Video.” To find many of these items within the Computer History Museum’s collection, a researcher would need to know exactly what system they were looking for in order to either find it in the catalog or identify it from a vaguely specified catalog entry. However, in the case of the EyePhone, neither the words “EyePhone” nor “virtual reality” appear anywhere in the catalog record’s description of the item, so a researcher would likely be unable to find the device in the catalog regardless of whether they knew exactly what brand of headset they were looking for or if they were searching for virtual reality objects in general. My search queries through the Computer History Museum’s online catalog showed the need for standardized terminology and key word descriptions when describing VR artifacts, as well as for catalogers to perform research on the items to add accurate descriptive metadata to these records. These metadata and cataloging practices would make virtual reality objects more discoverable for researchers.

One benefit of the Computer History Museum’s catalog, however, is that it links related items. Thus, peripheral input devices and cables are linked to the entry of the head mounted display that they are compatible with. This cataloging practice enables the discovery of all of the various hardware components that make up a complete virtual reality system (in cases where the institution has acquired all of these objects). If someone were to reconstruct a computing environment for using any of the headsets, they would be able to locate all of the accompanying equipment for the complete system. This information would also help a researcher understand all of the different hardware components of a virtual reality system and how they are connected together.

Searching the Living Computers: Museum and Labs catalog proved to be easier in terms of discoverability. All twenty-three of the virtual reality headsets, as well as all of the peripheral accessories and virtual reality-related materials in their collection appeared when searching for “virtual reality”, and the number of VR headsets I found was also confirmed when I spoke to Cynde Moya, the museum’s librarian and archivist. As such, searching the Living Computers collection was significantly easier, as all of the virtual reality headsets and other related accessories and documents all included “virtual reality” as keywords.

Moya creates MARC records for all of the assets in the museum’s collection. For her work, she deemed the most important metadata fields to be “title”, “date”, and “manufacturer”, and also prioritized provenance information such as where the collection came from and when it was accessioned.[64] The online catalog also includes information such as the physical dimensions of the item (including the VR headsets), barcode numbers, and the storage location of the item or if it was currently on display in the museum. In terms of the VR headsets at Living Computers, I found that none of their records were linked to records for any accompanying accessories or peripheral devices like the Computer History Museum’s records were. When I asked Moya about this, she responded that, if they were to receive a manual for a device or any software, the

[64] Moya

records for them would typically be linked. As Living Computers currently does not have any accompanying software or documentation for their VR devices, none of the records for the VR headsets had any other collection items that they could be linked to in the catalog.

The records for the VR headsets in the Living Computers catalog all included a note on the device's condition. In most cases this was just a one-word description such as "excellent" or "good." I asked Moya what it meant for a headset to be in "excellent" or "good" condition. Did it refer to just the superficial appearance of the headset or did it denote the functionality of the device as well? Moya informed me that the condition note refers solely to the headset's physical appearance. None of the VR headsets in the Living Computers collection have been tested and it is currently unknown how many of them, if hooked up to an appropriate computing system or video game console, would actually be functional.[65]

Examining the catalog records for the virtual reality headsets within these two collections demonstrated the importance of accurately describing and using a consistent controlled vocabulary for virtual reality equipment in order to make it more discoverable. This exercise also highlighted the need for catalogers, archivists, and preservationists to research the materials in their collection in order to appropriately describe them and make them more discoverable for researchers, such as in the case of the EyePhone headset in the Computer History Museum's collection, whose record lacked the words "EyePhone" or "Virtual Reality" anywhere within the item's description. Using appropriate descriptive metadata and adopting a metadata schema that has appropriate fields for virtual reality will be vital in terms of preserving the medium and making it accessible to researchers.

[65] Ibid.

Beyond catalog records, I also examined how virtual reality devices were displayed and exhibited at these two museums, as exhibitions are how members of the public view and learn about these artifacts from VR's history.

VR as an Object: Exhibition of Virtual Reality Headsets in Technology Museums

As both the Computer History Museum and Living Computers: Museum and Labs do not currently have any virtual reality software, they cannot exhibit their virtual reality holdings as part of an interactive exhibition. Instead, the pieces of VR equipment are displayed as inert artifacts, rather than interactive experiences. The Sword of Damocles is exhibited at the Computer History Museum inside of a glass display case. Twenty-two of the twenty-three headsets in Living Computers' collection are also on display in the museum. They are head-mounted displays from various moments in the history of VR, from 1990s-era devices like a VMX-1 and a Virtual Boy to examples of today's HMDs like the Oculus Rift and the PlayStation VR. These devices are all housed in a glass enclosure, through which guests can look at the devices. The one exception to this is the twenty-third headset in the collection: an HTC Vive. This headset from the current era of virtual reality HMDs is part of an interactive exhibit where visitors can use it to play virtual reality games hosted in the Steam library, accessed via cloud services.[66] However, Moya did not consider the games that users could play on the HTC Vive as part of the museum's collection.[67]

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[66] Steam is a cloud-based video game subscription service by the company Valve. Users can purchase and download video games from it and play them on a computer (or through a virtual reality headset, if they are downloading a VR game). Using a service like Steam, the user is not actually purchasing the game itself, but rather a license that allows them to play it. Cloud-based subscription services like Steam pose a preservation challenge, as rights issues will apply to these games.

[67] Moya

When viewed through a glass display case, the headsets become divorced from both their content and their intended use. These devices were made to be interacted with, not merely looked at. This type of display is perhaps more appropriate for a unique, one-of-a-kind, historical artifact such as the Sword of Damocles, which may be too fragile or dangerous (considering its weight) for users to interact with. In the case of all of the other, mass-produced headsets in these collections, a glass display case is quite unfortunate, as this presentation method tells us little about the devices, what kind of content was created for them, or how users interacted with them.

The most significant discovery made during this investigation was that while both collections include VR hardware devices, neither institution had any software to run on them. The implications of this collecting practice for the current wave of virtual reality will now be discussed.

A Rift Between VR Hardware and VR Content

Preserving virtual reality needs to encompass more than just saving physical objects. Just looking at an inert head mounted display inside of a glass case tells us little about how these items were used and the worlds users could access through them. According to interactive media artist and early VR pioneer Myron Krueger, “The welter of problems that must be solved to perfect virtual reality and the myriad technologies that are being investigated as possible solutions are not a menu of issues that can be addressed à la carte. Virtual reality is more than the sum of its components; it is fundamentally a system technology.”[68] As such, virtual reality works need to be treated as more than the sum of their parts.

Virtual reality is a complex system with interdependent relationships between hardware,

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[68] Foreword to *Virtual Reality Technology*, xi

software, content, and user interaction. It should not be treated solely as a physical object or artifact, as digital files make up the content that is viewed through the lenses of the headset and specific software may be required to play the content. Furthermore, other hardware components such as a computer or cell phone, as well as peripheral accessories like haptic gloves or video game controllers are required to both display the content through the goggles and enable users to interact with it. To use a metaphor from a film preservation perspective, preserving virtual reality equipment without its accompanying software would be akin to preserving kinetoscopes without any regard for preserving the films that once played on them. From a media art conservation standpoint, this practice would be analogous to preserving a CRT television without the video art piece that was created to play on it. These same concepts apply to virtual reality preservation as well. Preserving a VR headset on its own provides little understanding of the virtual reality system as a whole, the content that users could see through the display, and the experience of interacting with the VR system.

Moving forward, collecting institutions will need to understand both the software and the hardware and how they work together, thus preserving the content and the experience along with the hardware objects. The current wave of VR should not go the way of legacy VR. As the technology continues to develop, it is important to start thinking about and implementing digital preservation strategies now so that VR content can be experienced in the future, and researchers can gain an understanding of the software as well as the hardware. An examination of the different varieties of virtual reality content and strategies for dealing with the software and interactive components of virtual reality will be presented in the following chapters. In Chapter 4, I will outline the different types of virtual reality content and file formats, considering possible target file formats for preservation. In Chapter 5, I will evaluate the merits of existing preservation strategies such as migration and emulation, and how they could be utilized when preserving virtual reality material.

Chapter 4: Types of Virtual Reality Content and Preservation Challenges

As discussed when defining virtual reality in Chapter 1, the words "virtual reality" can be used to describe several different types of content. It can encompass 3D models, 360-degree video, and software applications such as video games. As I have discovered through my research, these different varieties of VR are fairly siloed from one another. For example, websites, articles, and scholarly journal articles that discuss 3D models tend not to cover video games or 360-video, and vice versa. Information about one variant of VR is typically found in entirely different places from information about another variant. This makes it difficult to understand what virtual reality content can be, and what types of file formats it can manifest as. A cultural heritage institution acquiring virtual reality materials will thus need to understand what the content is before considering preservation strategies for it. In this chapter, I will discuss the characteristics of different types of virtual reality content and file formats and consider preservation challenges for each.

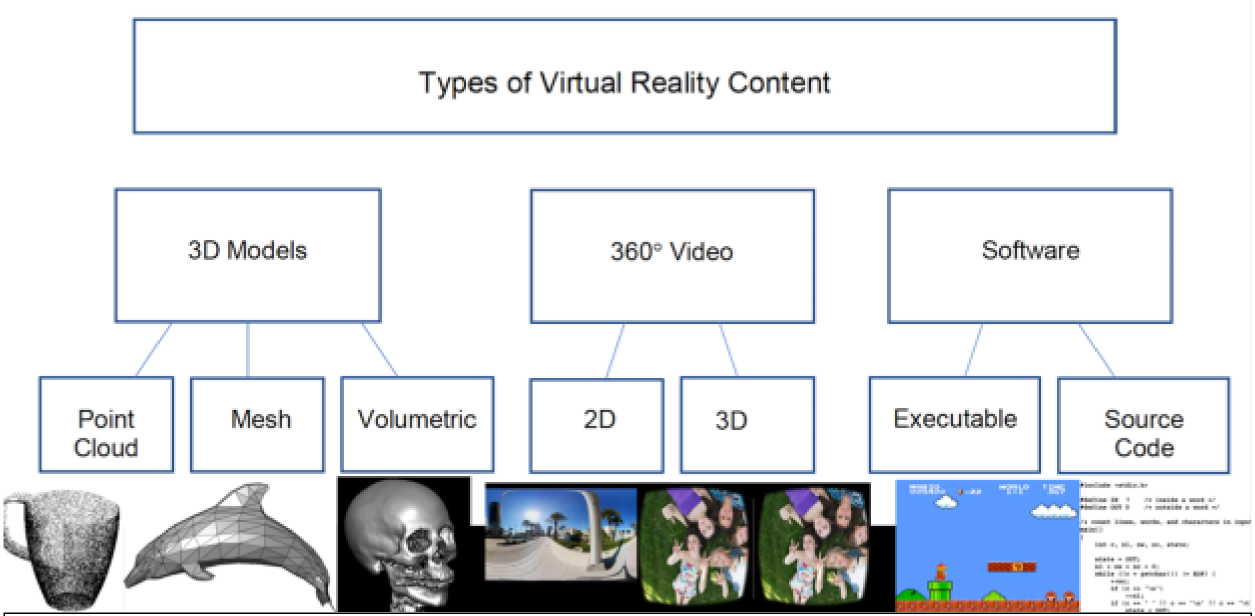

Figure 4.1: A Model for Understanding Virtual Reality Content Types

To help visualize and understand the different varieties of VR content, and what they can each encompass, I created the model depicted in Figure 4.1. When considering the different types of virtual reality content that a collecting institution could encounter— including 3D models, 360-degree video, and software—there are a variety of different types of content and file formats that can become the object of preservation. Three-dimensional models can take the form of point cloud data, mesh models, and volumetric models. Three-hundred-and-sixty-degree video can be either two-dimensional (flat/monoscopic) or three-dimensional (stereoscopic). When thinking about software-based VR content, cultural heritage institutions could preserve the playable executable file as well as the source code.

In this chapter, I will describe 3D models, 360-degree videos, and VR software, and the various forms they can take. As virtual reality content includes audio components as well as visual, how VR audio works and its various formats will also be covered. I will also provide an overview of different file formats for each content type, and discuss preservation considerations and challenges for each. By doing so, I aim to clarify what types of content virtual reality can encompass as well as the various types of file formats archivists and conservators will actually be preserving when working with virtual reality systems, and make recommendations for target file formats for preservation.

3D Models

One type of content that can be viewed through a virtual reality headset is three-dimensional models. This can include architectural models for engineering or cultural heritage purposes, 3D scans of the human body for medical research, character models for animation or video game design, as well as other quantitative data sets, such as charts and graphs presented as three-dimensional representations. When virtual reality is discussed as a tool that has the power to transform a wide array of industry practices, this is in part due to it being an excellent medium for viewing three-dimensional models from every possible angle.

Three-dimensional data can take several different forms: point cloud, polygonal mesh, and volumetric models. Point cloud models appear as sets of data points in a three-dimensional coordinate system. Visually, this looks like a field of dots that, when rotated, appears to have depth to it. A polygon mesh is a, "…collection of vertices, edges and faces that defines the shape of a polyhedral object in 3D computer graphics and solid modeling"[69] The data points making up the vertices and faces of a polygon mesh create a wire-frame-like model. Meshes tend to be hollow and represent only surface information (there are no data points on the inside of the model), and are thus an efficient way of creating convincing 3D models, such as character models for animated works and video games. The surfaces of meshes can also be rendered in different ways to create textural and lighting effects. Volumetric models offer the highest degree of complex data representation, and also require the most computational power to visualize. Volumetric models are comprised of solid blocks of data, which includes mapping the external surface as well as internal structure of the digital object. As such, volumetric models can be viewed in slices and planes, and are thus well-suited for the medical (e.g. locating a tumor in an MRI scan of body tissue) and engineering (e.g. drafting a model for a new building) fields where this kind of complex data needs to be represented.[70]

In addition to these different types of 3D models, there are a wide variety of different file formats the data can be stored in. Researchers at the National Center for Supercomputing

[69] "Polygon Mesh." Wikipedia. https://en.wikipedia.org/wiki/Polygon_mesh
[70] "Volumetric Imaging." PS-Medtech. http://ps-medtech.com/volumetric-imaging/

Applications at the University of Illinois at Urbana-Champaign identified 140 different file formats for 3D models.[71] This includes some proprietary file formats developed by companies that no longer exist. Those file formats will be particularly at risk of becoming unrenderable if preservation actions are not taken, since the software to render them is no longer being maintained by the developers. The report also includes 3D model file formats still widely in use today, both open-source and proprietary. Though the Urbana-Champaign report does not specify which ones or how many, the researchers mention that some of these file types can be identified using the DROID or PRONOM file format identification tools.[72] Discerning which 3D model file formats can be found in those directories will be helpful in determining target file formats for preserving 3D models.

Some of the more common 3D model formats in use today include: .obj, .dae, .ply, and .fbx. Zack Lischer-Katz, a Council on Library and Information Research (CLIR) fellow in Data Curation at the University of Oklahoma, is currently exploring the sustainability of the aforementioned 3D model file formats for meshes, as well as metadata schemas for them.[73] The .obj format is widely adopted in production and is one of the simpler 3D model formats to render. However, it is limited in that it only contains information for the mesh structure itself, and not any information about its surface texture or color. Texture and color information is stored in separate image (.jpg or .png) and .mtl files. Using .obj as a preservation format would thus also necessitate preserving three separate files to preserve one, complete 3D model. Another

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[71] Kenton McHenry and Peter Bajcsy. *An Overview of 3D Data Content, File Formats and Viewers*. University of Illinois at Urbana-Champaign, 2008.
[72] Ibid.
[73] For updates on the progress of this research, refer to the project blog "VR Preservation Project: Studying the Preservation of Virtual Reality at University of Oklahoma Libraries" http://vrpreservation.oucreate.com/

concern with .obj is that there is no standard way to embed metadata in it, meaning a fourth file containing sidecar metadata information would have to be saved along with the three files describing the model's shape, color, and texture. In Lischer-Katz's work, he is exploring alternate 3D model file formats for preservation purposes, primarily the .dae, .ply, and .fbx formats.

One potential preservation format for 3D models is .dae, which is more commonly referred to as the COLLADA (CoLLAborative Design Activity) format. COLLADA is a royalty-free open standard. In 2005, the Khronos Group, a consortium of 3D software and hardware developers, adopted COLLADA as an industry standard.[74] The format is based on XML and allows for embedded metadata. With these factors in mind, .dae could assimilate well into existing digital repositories at cultural heritage institutions. COLLADA is also seeing increasing adoption by VR content and hardware developers, which may make it more sustainable in the future. The .ply format is another open format that is widely used in production and .fbx is proprietary, but also fairly prevalent in production processes as it allows for creating animations. The sustainability of these various formats is currently being explored in Lischer-Katz's work with Oklahoma University Libraries. Currently, COLLADA appears to be the best candidate for preservation files as it is an open standard that is seeing increasing adoption, and it allows for embedded metadata.

Preserving virtual reality 3D model content will be a challenge cultural heritage institutions will have to face, in large part because there are an enormous number of different file types and no accepted, widely-adopted file formats for preservation currently exist, and no best

[74] Wojciech Cellary and Krzysztof Walczak. "Interactive 3D Content Standards." *Interactive 3D Multimedia Content: Models for Creation, Management, Search, and Presentation*. (Springer, 2012): 25-26.

practices for archiving this content are yet in place. Though there are currently no standards in place for 3D model preservation file formats, research such as that currently underway at University of Oklahoma Libraries can potentially yield agreed upon and widely-adopted formats in the future.

360-Degree Video

One type of content that has been advertised under the terminology "virtual reality" is 360-degree video. While some decry this categorization as 360-degree video does not allow for any user mobility within a virtual space, this type of content has been absorbed under the larger umbrella of "virtual reality." As noted by technology journalist Stuart Dredge:

> The terms '360' and 'virtual reality' are often used interchangeably, but there are important differences. The 360-degree photos and videos are panoramic pics and videos that have been stitched together, so you can turn your head to look around you. But these aren't virtual worlds: you don't have free movement to explore them as you do in full virtual reality experiences.[75]

Rather than being able to wander through a computer-generated, virtual realm, with 360-degree video, the viewer is rooted to a single, fixed location and the video content plays around them. However, the viewer can turn their head from side to side and up and down and see video surrounding them on all sides. Thus, the video surrounds them in a full 360-degree sphere. For this reason, 360-degree video is also known as spherical video.

It is possible to view 360-degree video files on a regular, flat computer monitor. In these videos, one can look at them in a media player, click on the video with their mouse and drag the image in order to see it from other angles. However, this is a rather cumbersome and unintuitive process and one does not get the full, immersive feeling of the work when viewing it in a web

[75] Dredge.

browser or desktop application. As such, 360-degree video is most optimally viewed through a virtual reality headset where the viewer can be more immersed within the imagery, and look around at the panoramic moving images by moving their head from side to side, as they would when surveying a real-world landscape. VR devices from the Oculus Rift to the Google Cardboard are all capable of playing 360-degree video files as well as more interactive, software-based content.

Cameras create 360-degree videos by stitching together many flat videos and arranging them into a panoramic, spherical shape (these videos are typically shot using multiple cameras arranged in a circular pattern, with the lenses emanating from a central focal point, and the discrete flat images are then projected onto a sphere). As Andrea Hawksley of the virtual reality research team eleVR notes, "All of our films and formats and file types are for storing flat video information. This means that even if a single camera could record spherical video all the way around it, it would still have to make the world flat to store that information."[76] While there is no way to completely flatten a sphere into a flat shape without introducing distortion to the image, there are several different methods of sphere-to-plane projection. I am briefly going to discuss two of these methods: equirectangular projection and cube projection.

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[76] Andrea Hawksley. "Are you eleVRanting, or am I projecting?" eleVR.com. September 25, 2014. Accessed April 15, 2017. http://elevr.com/are-you-elevranting-or-am-i-projecting/

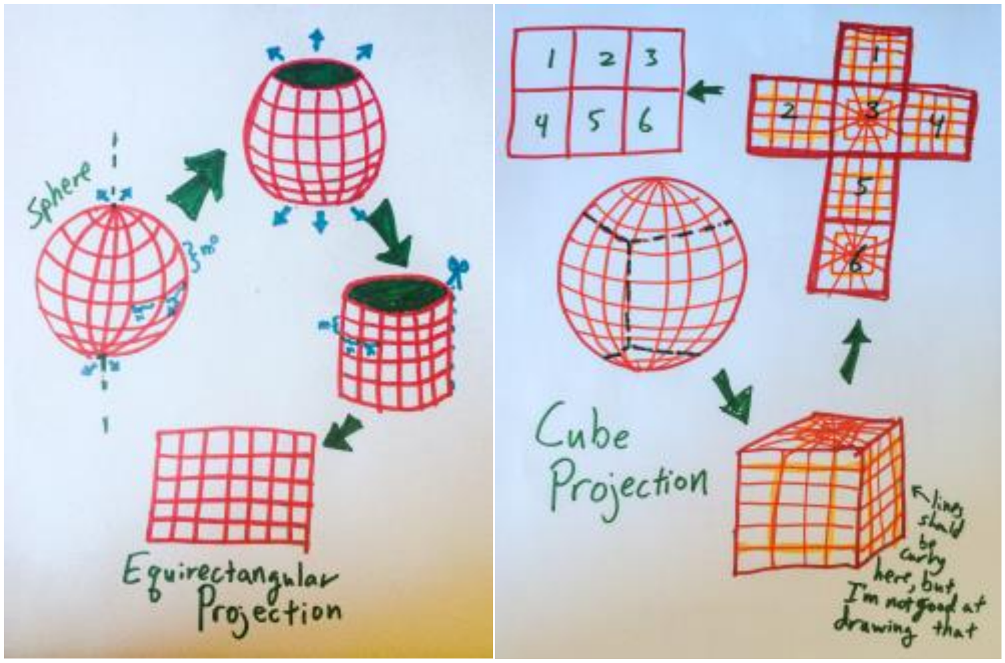

Figure 4.2: Visual Representations of Equirectangular and Cube Projections
(eleVR - http://elevr.com/are-you-elevranting-or-am-i-projecting/)

In an equirectangular projection, the spherical image is transformed along longitudinal lines, turning them into straight vertical lines with equal spacing in between. This squishes the sphere into a cylindrical shape. From there, the latitudinal lines are straightened out into horizontal lines with equal spacing in between them. For equirectangular models, it is helpful to think of the process of flattening a globe into a two-dimensional wall map. Equirectangular projections create distortion towards the top and bottom (i.e. the north and south poles) of the image, and maintain the original aspect ratio in the center (i.e. the equator).[77] VR cameras tend to output video files in an equirectangular format, and most current players that support 360-degree videos support this mapping.

[77] Emily Eifler. "Editing Spherical 3D Video in Premiere and After Effects, A Design Document." *eleVR*. September 10, 2014. Accessed April 15, 2017. http://elevr.com/editing-spherical-3d-in-premiere-and-after-effects-a-design-document/

With cube maps, the spherical video is first mapped into a three-dimensional cube shape. Then, the cube is simply unfolded into a flat plane. The flat projection can then either be stored in its unfolded t-shape, or the six squares can be rearranged into a rectangular for even more efficient storage. This transformation can be visualized with an actual 360-degree image as such:

Figure 4.3: Moving from an equirectangular map to a cube map
(FaceBook Engineering Blog - https://code.facebook.com/posts/1638767863078802/under-the-hood-building-360-video/)

Of course, the flat cube map will then be decoded by the video player to recreate the spherical video effect. Cube mapping is considered to be more computationally efficient than equirectangular mapping, and is how video games store content as well. Though cube maps still produce a degree of image distortion (as there is no mathematically possible way of equally distributing a spherical video into a flat plane), the information is distributed more evenly than in equirectangular projections, lessening the visual presence of distortion.[78]

Aside from projection maps, file formats for 360-degree video are generally the same as regular video formats such as .mp4, .mkv, .mov, and .avi. Spherical videos can be either two-dimensional (monoscopic) or three-dimensional (stereoscopic).[79] With 3D, stereoscopic content,

78 Hawksley
79 “Supported Video Formats by VR Headsets.” Accessed December 12, 2017. http://www.brorsoft.cn/tutorial/vr-headset-supported-video-formats.html

the video appears as two separated, slightly offset frames that become unified into a single 3D video image when viewed through a VR headset. Both 3D and 2D spherical video content can also be encoded in MPEG-4 in the h.264 or h.265 codec.[80]

It should be noted that different VR headsets support different varieties of video file formats, so transcoding may be necessary if the content is desired to be viewed across multiple headset models. Which file formats different headsets support needs to be considered when choosing formats for preservation masters and access derivatives. I have included a chart of VR headset file format support for the most popular HMD models in Figure 4.4 below:

VR Headset Model	Supported 360-degree Video File Formats
Oculus Rift[81]	.mkv, .mp4, .avi, .wmv
HTC Vive[82]	.mkv, .mp4, .mov, .divx[83]
PlayStation VR[84]	.mkv, .mp4, .avi, .mts, .m2ts
Samsung Gear VR[85]	.mkv, .mp4, .avi, .wmv, .m4v, .3gp, .3g2, .webm, .asf, .flv
Google Cardboard	Depends on type of cell phone used

Figure 4.4: Chart of VR Headset Models and Supported 360-Video File Formats

[80] Nick Kraakman. "The Best Encoding Settings for Your 4K 360 3D VR Videos." *Purple Pill*, December 2, 2015. Accessed April 9, 2017. https://purplepill.io/blog/best-encoding-settings-resolution-for-4k-360-3d-vr-videos/

[81] For more information on file formats for the Oculus Rift, see https://appuals.com/convert-2d3d-videos-oculus-rift-vr/

[82] For more information on file formats for the HTC Vive, see https://www.viveport.com/apps/ed3adb70-9390-4ca3-863a-26b5fd08b8d7

[83] The HTC Vive also supports sidecar files for subtitles in the following formats: .srt and .ass

[84] For more information on file formats for the PlayStation VR, see http://manuals.playstation.net/document/en/ps4/music/mp_format_m.html

[85] For more information on file formats for the Samsung Gear VR, see https://support.oculus.com/help/oculus/1765950523674738

The most widely compatible file formats for 360-degree video are .mkv and .mp4. Both of those formats appear to be able to play on all of the most popular models of VR headset currently available. With this information, preservationists can be aware of which devices their preservation and access files will be able to play on.

In archival practice, the preservation master file is ideally an uncompressed video format to preserve the highest degree of visual information possible. Codecs like h.264, that compress video, are generally used as access files rather than preservation files. To understand potential preservation formats for spherical video, I contacted Andrew Scherkus, a member of the Google Spatial Media Group that is actively working on standards for spherical video. He noted that uncompressed, high-resolution, stereoscopic 360-degree video will cause file sizes to be quite massive, and storage is a huge consideration for archivists. I inquired whether a lossless codec such as FFV1 or JPEG200 could be implemented to result in smaller file sizes with no loss to image quality. Scherkus responded that lossless codecs might be feasible, though storage costs may still be prohibitive. He suggested exploring storing the information as a cube projection since equirectangular projections tend to result in larger file sizes. According to Scherkus, "…cube maps can technically represent the same video with less total pixels. The conversion is not 100% lossless though. Whether the industry should standardize around (say) cube maps vs. archivists transforming to (say) cube maps to save on storage space is an interesting question."[86] Thus, one way preservationists can think about dealing with 360-degree video is to use a more efficient projection mapping, rather than a more efficient (lossy) video encoding. Further research comparing the different projection mappings within different encodings, assessing the

[86] "Andrew Scherkus. "Re: Questions on Standards for VR." Message to Savannah Campbell. January 12, 2017. Email.

image qualities and file sizes, should be performed before cultural heritage institutions begin determining which projection mappings and video encodings to use for preservation purposes.

I will further discuss the work of the Google Spatial Media Group in Chapter 6. For now, I will note that the technical metadata specifications for 360-degree video that the group is currently working on supports the MP4 and Matroska (.mkv) file formats. These are also the two 360-degree video file formats that are most widely supported by all of the major VR headset models. Currently, Matroska is undergoing formal standardization through the Internet Engineering Task Force. These format specifications are being developed by media archivists, so Matroska will be tailor-made for archival use. When the Matroska format becomes formally standardized, support for 360-degree video will be built into it.[87] With this in mind, cultural heritage institutions should consider Matroska as a potential wrapper for 360-video preservation master files.

Virtual Reality Software

When it comes to interactive virtual reality software content like video games, the playable, executable file is really a package containing a wide variety of different file types and formats. A VR software package can include any of the 3D model formats and video formats previously mentioned, as well as audio files, text files, and data files defining how the software functions. Thus, when thinking about preserving software content, it is important to consider all of the individual files contained within the software package, and how they work together to create an interactive experience. All of the preservation concerns pertaining to all of the other

[87] Refer to Pull Request #53, submitted by Dave Rice, in the Matroska Specification GitHub repository. https://github.com/Matroska-Org/matroska-specification/pull/53

different VR file types and formats previously discussed will thus also apply to preserving virtual reality software.

Aside from the executable file that comprises the complete, playable video game, another potential object of preservation could be the source code: the human-readable, written commands that make up the executable program. The format of the source code depends on the language that the program was written in, making the file format the same as the file extension for the original script (for example, a script written in Python will have a .py extension). Depending on the game engine used to build a virtual reality game, the programming language for it will vary. A game engine is a specialized suite of tools used to create video games.[88] Two of the most popular engines for building VR content are currently the Unity engine and the Unreal engine. Games built in Unity are programmed in the language C#, while content produced in Unreal is programmed in C++. However, it is possible that other VR applications will be programmed in languages other than C# or C++. Virtual reality content developed for the web, for example, could be based on Javascript and HTML.[89] Regardless of the programming language implemented, copies of the created source code should be saved in their original formats. Though it is possible to save source code in a standard text file format, this is not ideal. When saved as a text file like .txt, features of the code that make it more human-readable, like syntax highlighting, will be lost when viewing the code in a text editor. Additionally, saving source code in a .txt or other text format will also eliminate valuable contextual information, including information that easily identifies what programming language the code was written in (since that information could have quickly been discerned from the file extension of the original script). To preserve this

[88] Game engines can dictate how the game's graphics are rendered; how physics within the game works; sound, lighting, and animation effects; how memory is stored, and more.
[89] Mark Hellar. Personal interview by Savannah Campbell. February 13, 2017.

identifying and contextual information, the source code should simply be saved as its original script format.

One preservation consideration is that much of the virtual reality video game content and other VR software applications are available solely through cloud-based content libraries. The Oculus Rift has its own app store and content for the HTC Vive is available in the cloud-based video game subscription service Steam. Video games for the PlayStation VR can be downloaded through the PlayStation Network, and applications for phone-based virtual reality platforms are available through Apple iOS and Android app stores. In contrast to previous video game distribution models (purchasing a physical game cartridge or CD-ROM), when using a cloud-based service like Steam, the user is buying a license to play the game, not the actual game itself. As such, there may be licensing issues involved in preserving this kind of content within cultural heritage institutions. There is also the risk that if this companies drop support for virtual reality content and hardware, or if they go out of business like the VR tech companies in the 1990s did, this content may become inaccessible. There will not be an easy solution to tackling this problem, but it is a concern that virtual reality preservationists should be aware of.

Preserving software is a complex process and the best practices for doing so are continuing to be considered among archival communities. The next chapter of this report will further cover strategies for preserving software content. Digital preservation strategies such as migration and emulation will be considered for VR software, as well as adapting other video game preservation strategies for virtual reality content, will be discussed more granularly in Chapter 5.

Audio for Virtual Reality

Thus far in my discussion of virtual reality content, I have focused primarily on preservation issues related to its different visual aspects. However, VR is meant to be an immersive medium that engages the user on multiple sensory levels. Audio is an important aspect in creating the illusion of being in another place, and should not be ignored when considering how virtual reality content is preserved in cultural heritage institutions. According to Adam Somers, an audio engineer working with virtual reality content, "…audio is critical to an immersive experience within the context of VR. We consider audio to be 50 percent of the immersive experience."[90]

Audio for virtual reality works can be traditional stereo audio, or it can be ambisonic audio (also referred to as spherical audio or 3D audio). The effect of ambisonic audio works by mimicking the human head, and how the human brain actually processes audio information to localize where a sound is coming from. As we tilt our heads left or right, sounds will sound closer or farther away from us, depending on the position of our head, and how far away we physically are from the object emitting the sound. Ambisonic recordings emulate this effect by, "recording and reproducing surround sound in both horizontal and vertical surround from a single point source."[91] This can be achieved by either using software to manipulate numerous discrete audio sources, or be produced directly by recording using four microphones arranged in a spherical shape around a common center point.[92] This effect is best experienced through

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[90] Mona Lalwani. "Surrounded by Sound: How 3D Audio Hacks Your Brain." *The Verge*. February 12, 2015. Accessed April 15, 2017. http://www.theverge.com/2015/2/12/8021733/3d-audio-3dio-binaural-immersive-vr-sound-times-square-new-york

[91] John Leonard. "Welcome to the Wonderful World of Ambisonics." *A Sound Effect*. January 16, 2016. Accessed April 17, 2017. https://www.asoundeffect.com/ambisonics-primer/

[92] Ibid.

headphones and the ambisonics create the illusion of realistic, three-dimensional audio. As virtual reality headsets track the user's head position to determine what imagery to generate, they simultaneously do the same for the audio track.

Whether a virtual reality work is a 360-degree video or a fully immersive video game, the user has the freedom to look in any direction, regardless of where an important plot point may be occurring. Using spatial audio, developers can create sound cues to capture the user's attention and prompt them to look or move in a specific direction. This can be helpful in terms of storytelling, and allows time-based virtual reality content to progress forward without the user missing significant plot information.

Ambisonic audio is a flexible format and is "codec agnostic."[93] It is also infinitely extensible. Though ambisonic recordings require at least four regular audio tracks, an infinite number of channels can potentially be included. Audio resolution and fidelity increases as the number of ambisonic channels increases.[94] Anything more than four audio tracks is referred to as high-order ambisonics. This is possible because, unlike normal mono or stereo recordings, spatial audio does not represent the sound that should emit from different speakers, but rather the information for the entire sound field.[95] Though this is different than standard audio recordings, ambisonic audio can work within the same audio file formats.

One thing to consider when preserving ambisonic audio for virtual reality is that compressing the audio can significantly impact the effectiveness of directional sound cues. According to Steve Aukstakalnis, "Researchers and developers producing binaural recordings for

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[93] Andrew Scherkus, "Developing VR Media Technology." Presentation from DEMUXED Conference 2016. Video recording. https://www.twitch.tv/videos/94956817
[94] Ibid.
[95] Vi Hart. "Audio for VR Film (Binaural, Ambisonic, 3D, etc.)" *eleVR*. August 31, 2014. Accessed April 15, 2017. http://elevr.com/audio-for-vr-film/

virtual and augmented reality applications should always record and manipulate in an uncompressed audio format such as WAV or AIFF to capture and preserve the entire frequency spectrum."[96] As such, it would be good preservation practice to preserve audio for virtual reality works in uncompressed file formats such as WAV, FLAC, or AIFF.

A Rift in Virtual Reality Content Types

Before any preservation actions can be taken, a cultural heritage institution must first have an understanding of what kind of virtual reality content and file formats they have in their collection. Each type of virtual reality can be used within various industries, in a range of different contexts. With this being the case, preservationists will have to perform research to understand what type of VR content they are dealing with, as "virtual reality" can encompass video games, 360-videos, and 3D models, and the files may also have accompanying audio tracks as well.

Though there are currently no widely adopted file formats and standards for preserving virtual reality, some recommendations can be made for target file formats for each type of virtual reality content. Based off of Zack Lischer-Katz's research, the COLLADA (.dae) format appears to be the best candidate for preserving 3D models as it is an open, XML-based standard that supports embedded metadata. For 360-degree videos, Matroska (.mkv) is a good choice for preservation as the format is being standardized and developed by archivists, and is also supported on a large number of virtual reality headsets. For software, the executable file should be saved along with the source code in its original script format. In terms of ambisonic audio, an uncompressed audio format such as FLAC, AIFF, or WAV will be suitable for preservation

[96] Aukstakalnis, 155-156.

purposes.

This chapter aimed to provide an overview of the different virtual reality content types as well as some of the different file formats a collecting institution may encounter when handling a virtual reality collection. The next chapter of this thesis will now explore different preservation strategies that can be implemented to preserve the different types of file-based virtual reality content.

Chapter 5: Preservation Strategies for Virtual Reality

Virtual reality is a complex medium with a myriad of different components that need to be considered when developing preservation strategies for ensuring its long-term accessibility. The hardware, software, and supporting documentation, as well as the varieties of VR content outlined in Chapter 4, will all require different preservation approaches. As exemplified by the work of the Computer History Museum and Living Computers: Museum and Labs, collecting institutions have thus far focused mainly on preserving virtual reality hardware. This chapter aims to discuss ways that a complete VR system, including its software, can be preserved, and how it can be accessed. There are a variety of different existing digital preservation strategies that could be applied to virtual reality works, though they may have varying degrees of success.

In this chapter, the limitations of physically storing VR systems and maintaining obsolete hardware will be examined, and digital preservation strategies such as migration and emulation will be considered, as well as the ways they can be applied to the various components of a virtual reality system. Following the analyses of different preservation methods, I will also discuss practices from the fields of video game preservation and time-based media conservation. As both of those fields deal with the preservation of complex media systems, their practices can potentially serve as models for virtual reality preservation plans.

Physical Storage

Probably the most straightforward preservation strategy that can be employed is the “storage approach”: storing physical objects in a temperature and humidity-controlled environment to give the artifact a longer lifespan. Traditional archival institutions use this approach, which is a best practice for dealing with paper materials, celluloid film, and photographs. To extend this approach to virtual reality would encompass placing all of the virtual reality hardware (the headset, any input devices such as gloves, and possibly even a computer) in a climate-controlled vault. It would also constitute storing the physical-digital object (i.e. a hard drive or optical disc) that the source code or software are saved on. Of course, this is a passive approach to preserving something as dynamic as a computing system, where hardware and software technology progress at such a rapid pace that these items become obsolete very quickly. Placing an optical disc containing VR software in an acid-free sleeve in a cool and dry vault only accomplishes so much, and the carrier itself is subject to deteriorate over time and render the content stored on it unreadable. Locked away in storage, these VR objects may be "saved" in a material sense, but their content would quickly be rendered inaccessible, and the experience of actually exploring the virtual world would be lost.

Digital preservation requires a more active approach, which includes regularly monitoring files (such as by running checksums) to ensure that files remain readable and uncorrupted, as well as transferring digital files to reliable storage mediums. It can also entail migrating files to more sustainable file formats or creating emulators to play older media on newer computers. These strategies (migration and emulation) will be discussed later in this chapter, but first another approach will be considered that involves taking steps to maintain the VR hardware and run the software in its original environment.

Maintaining the Original Hardware: The "Technology Museum Approach"

Many technology museums, such as Living Computers: Museum and Labs, The Strong Museum's International Center for the History of Electronic Gaming, and the Museum of the Moving Image aim to preserve as much of the original look, feel, and behaviors of the interactive experience of a computing environment as possible by keeping the software running on its original hardware. This approach takes a more active role than the "physical storage" approach, and also allows for users to access these digital objects in museum exhibits, such as the ones at the aforementioned institutions that showcase vintage video games and computers. While this strategy enables visitors to have experience of using a software program on the hardware that it was designed to run on and gain a more accurate idea of what the game or application was like when it was first released, the "technology museum approach" does have several drawbacks.

As hardware becomes obsolete, replacement parts become scarce, and the individuals who know how to repair them retire or pass away, it will become increasingly difficult to keep vintage computing systems running. As noted in the *Preserving Virtual Worlds Final Report*, "Ideally, museums and collectors wish to preserve the original experience through maintenance and upkeep, but as hardware platforms age, it becomes more difficult to find repair parts. Furthermore, finding individuals with sufficient knowledge to repair such systems also becomes increasingly difficult over time."[97] While it may be advantageous to a researcher to experience software in its original hardware environment, this approach will not be sustainable in the long-term.

The human factor in this type of preservation is also difficult to maintain. Preserving the knowledge and skillset required to maintain historical computing hardware is probably the most difficult component of all. As Baker and Anderson observe:

> ...users tend to learn by building on tacit knowledge of systems which retain familiarity over generations of software/hardware, but seldom consider reading the operation manual for the latest piece of equipment unless they need specific information about new or changed functionality. However, such a continuity of understanding cannot be assumed

[97] Jerome McDonough, et al. *Preserving Virtual Worlds Final Report* (2010), 61.

when looking to the future.[98]

It cannot be taken for granted that the training and knowledge required to repair obsolete hardware will be carried to future generations. As such, the "technology museum approach" to preservation may not be viable as individual and collective knowledge of system maintenance and repair fades and machine parts become more difficult to replace.

Even if keeping software and media content running on its original hardware for as long as possible is desirable, obsolete technology cannot be expected to function indefinitely. With this being the case, archivists, preservationists, and conservators should consider separating the content (software) from the carrier (storage medium) in this instance. If the software is preserved, it could be run on newer hardware in the future. Though this will provide a different user-experience, it would at least ensure that the virtual reality content could continue to be accessed in the future. Additionally, saving digital files in their original format may not be enough to ensure their long-term accessibility because, like with hardware, file formats can also become obsolete. Thus, archivists and conservators need to take additional measures to ensure that digital content is preserved. The two predominant techniques of preserving and maintaining access to digital objects like software are migration and emulation.

Migration

Migration is the process of "…moving code from one target platform to a newer or better target platform that is capable of running the software application."[99] In practice, this involves transcoding an older file to a newer, more sustainable file format. While migration is the

[98] Drew Baker and David Anderson. "Laying a Trail of Breadcrumbs—Preparing the Path for Preservation." *The Preservation of Complex Objects (Volume 1: Visualisations and Simulations)*, (University of Portsmouth, 2012): 22.

[99] McDonough, et al. 78.

preferred preservation strategy for simple file types such as text-based documents like ASCII or PDF files or even video files, it is a more difficult strategy to implement when dealing with complex digital objects such as video games, net art, and virtual worlds. Migration of these types of digital objects is possible, however, if one has access to the original source code or the binary (the ones and zeroes that the video game is comprised of).

When dealing with software objects such as video games, there are two types of migration that can be employed: source migration and binary migration. Source migration, also known as “porting”, can be performed if one has access to the software’s source code, along with other assets that define how the game or virtual world functions (such as graphics files and information about user input and operating system compatibility). Source migration is typically more viable when the digital objects are being transferred to equipment that has similar computing architecture (type of processor) as the original hardware, though it is possible to perform source migration to a target computing environment different from the original. The other type of migration, binary migration, requires access to the program’s binary, as well as the types of assets that define the look and navigation of the program. Binary migration is more susceptible to changes in computer architecture than source migration, and is most effectively utilized in cases where the target platform is backward compatible with the original platform.[100]

While possible to use either of these migration strategies to preserve virtual reality software components, it may not be feasible for most cultural heritage institutions due to the high cost involved. Migrating complex digital objects is a labor-intensive and resource-intensive process that may not be, according to Baker and Anderson:

> …a viable option particularly within an institutional context. Large scale preservation activity is always expensive, but the time, equipment, and expertise required to migrate

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[100] McDonough, et al. 79

> (or port), for example, interactive video games from one hardware system to another to ensure that they look and behave exactly the same on each platform is completely beyond the means of any library or archive.[101]

Thus, some collecting institutions may not find migration to be the best preservation strategy for their virtual reality materials, though this strategy has other drawbacks as well.

In order to perform migration with the goal of providing long-term access to a digital object, the target file type must be sustainable and widely accepted as a de facto preservation standard. Currently, there are a large number of different file types being used in the creation of virtual reality games, movies, and programs. As discussed in Chapter 4, there currently are no official standards for virtual reality file formats that have been widely accepted by developers and no standards for VR have been implemented by media preservationists. David C. Brock, director of the Center for Software History at the Computer History Museum, suggests that migration will not be possible, "…unless people create virtual worlds with some sort of standards… If there are standards, there would be the possibility for migration, but only if those standards are widely adopted."[102] As standards for VR (in terms of file formats, metadata, and production practices) have not yet become widely adopted, it may be too soon to consider migration as a viable preservation strategy for virtual reality works and systems. Developing standards for virtual reality, which will further be examined in Chapter 6, will be essential for preservation planning, especially if migration is to be considered.

Emulation

While migration is best-suited for simple digital file types, emulation has generally been considered a more acceptable approach for more complex digital objects like video games and

[101] Baker and Anderson, 16
[102] Brock

software. Emulation involves developing software to that allows older programs to run on newer hardware, by making the newer hardware behave like the legacy computing environment being emulated. As opposed to the migration approach, where the focus is on the individual digital file, emulation is more concerned with the original hardware and computing environment the digital object was first experienced in. Emulation can be an advantageous preservation strategy because, "…if done properly, it completely bypasses any concerns about file-format inflation and complexity. If the emulator performs as it should, then any file which ran on the original platform, whatever its format or complexity should perform under emulation exactly as it did on the original."[103] Another benefit of emulation is that it mimics legacy hardware without actually using it. In the case of an interactive museum exhibit, if patrons used an emulator to experience the digital work, no wear and tear would be inflicted on the original hardware. In cases where the original hardware is too rare or fragile to be used on a regular basis, emulation would allow for access to the software in an environment removed from the legacy hardware.

However, emulation is not without its drawbacks. Emulators themselves also will need to be preserved and updated. As Baker and Anderson note, "…emulators are digital objects in their own right, and are just as subject to being rendered inaccessible when the hardware platform on which they were designed to run becomes obsolete…"[104] Thus, if a cultural heritage institution chooses emulation as their strategy for preserving virtual reality, or any other complex digital media, the emulator itself must be preserved and maintained to ensure access.

As of yet, no emulators have been made for any of the virtual reality devices currently on the market.[105] Though this has not yet become necessary, as devices such as the Oculus Rift,

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[103] Baker and Anderson, 16
[104] Baker and Anderson, 17
[105] Mark Hellar. Personal interview by Savannah Campbell. February 13, 2017.

Samsung Gear VR, HTC Vive, and PlayStation VR have only been available to consumers since 2015 or 2016 and are still the current platforms for virtual reality. However, as the consumer virtual reality devices of the 1990s show, when technology becomes obsolete, its content can be lost if preservation actions are not taken.[106] So, while it may not yet seem practical or necessary to build an emulator for the Oculus Rift at this point, it is something that should be kept in the back of developers' and preservationists' minds so current virtual reality content can be accessible in the future.

Migration, Emulation, and Issues of Authenticity

One concern with both migration and emulation is how authentic the preservation endeavor is in maintaining the look and feel of the original digital object. Even when the utmost care has been taken during the preservation process, it is still possible for the migrated or emulated file to appear or behave differently than the original. Colors and textures originally viewed on cathode ray tube displays will appear altered on today's LED, OLED, and LCD monitors, and subtle changes to character movement (motion blur) or the quality of the audio may occur. As Anderson and Baker note: "…it is not uncommon for files originally written for one computer system to appear slightly differently on a new system… While in some cases, this may not be important, in others it may crucially alter the intellectual content or meaning in ways which are not systematically predictable."[107] They go on to speculate that transcoding files from

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[106] In my research, I also attempted to find emulators for older VR games from the 1980s and 1990s. I was only able to find one emulator, and it was for the Nintendo Virtual Boy. That particularly emulator, however, displayed the game in black and white, rather than in the Virtual Boy's signature black and red display. While the games could be played in this emulator, their appearance was fundamentally altered, which demonstrates issues of maintaining authenticity when using emulators for preservation purposes.

[107] Baker and Anderson, 16

one format to another, as is part of the migration process, is liable to introduce these kinds of authenticity differences into the digital object. However, these same issues can occur with emulation as well. As computing technology may have advanced exponentially between the creation of the work being emulated and the production of the current hardware being used to view it, "The extreme disparity between the speed of current and historical processors can lead to problems with rendering speed, a problem that is unfortunately not trivial to solve."[108] Emulators may be built to run legacy software, but in practice they may not render it in exactly the same way the original hardware did and could potentially alter the look, feel, and functionality of the digital object.

Though migration and emulation both have the potential to introduce changes that alter the character of the digital object, this is not a foregone conclusion. Though a preservationist strives to reproduce the original material in the most faithful manner possible, migration and emulation remain the most viable digital preservation strategies to maintain long-term access to digital material. In my discussion with David C. Brock, he told me, "Let's not let the perfect be the enemy of the good."[109] Preservationists should aim to maintain accessibility to the digital object by moving it into file formats or computing environments that can display its content. Though there is a risk of altering the digital material, both in significant and in barely perceptible ways, this should not deter cultural heritage institutions from trying these strategies. Access to a digital facsimile that is a close enough approximation to an original work is better than losing the work entirely.

This is not to say that preservationists should not strive to create the most accurate

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[108] Oya Y. Rieger and Tim Murray, et al. *Preserving and Emulating Digital Art Objects* (Cornell University Library, 2015): 15.
[109] Brock

preservation files as possible. To mitigate issues of authenticity when emulating or migrating a virtual reality work, having access to the original hardware will aid in preservation. If possible, to achieve the most accurate representation of an original software, archivists and conservators should first set up the original computing system in its entirety (headset, computer, peripherals, and software content) and observe the behavior of the work in its original environment. This can then be used as a reference for what the emulated or migrated software should look like, sound like, and how it should function. Then, the preservationists can perform side-by-side comparisons of the original and recreated versions of the software to create the new, digital preservation object. Additionally, if any changes to the look and feel of the work are unintentionally introduced in the emulation or migration process, preservationists should document these changes. If a perfect emulated experience or migrated preservation master file is unobtainable, then at the very least a record can be kept of the reasons why through careful, detailed documentation by the preservationist or conservator. Documenting the preservation work done and noting any changes to the original will help future researchers and users contextualize and interpret any significant alterations to the work.

A Multi-faceted, Holistic Approach to VR Preservation

As previously stated, virtual reality is a complex system with both physical and digital components that merit consideration for preservation. There are a multitude of different file types associated with virtual reality, and some may best be preserved using one method over another. In addition to the hardware and the software, preserving other kinds of documentation will be important in ensuring that a virtual reality environment can be accessed in the future and understood in its historical context.

As noted in the Arts and Humanities Data Service's *Creating and Using Virtual Reality: A Guide for the Arts and Humanities*, archiving virtual reality does not solely constitute preserving the files that make the virtual environment, but also, "…original data files and supporting documentation such as the project report. The best strategy is for all these digital data to be systematically collected, maintained, and made accessible to users operating in very different computing environments."[110] Collecting this VR-related documentation will be key in understanding the system's development, how it should be displayed in the future, and possibly its relationship to the larger virtual reality and cultural zeitgeist of the time it was created. These materials will also require preservation treatment, and will likely need to be preserved in a different manner than the software. The ADHS Guide also notes that:

> For many projects, an acceptable alternative to archiving the VR world itself, which may be both difficult and uncertain for proprietary or non-standard formats, might be to break down the VR into its original source files. With this approach, the source file would be deposited in standard formats together with screen shots of the world and a detailed description of how to put the elements back together to recreate the application[111]

While I maintain that the complete virtual reality system should aim to be preserved, archiving the source code in this manner, along with photographic or video documentation or what the virtual environment looks like and how it behaves, will aid in providing supporting materials that future researchers and users can access to further understand virtual reality applications and how users interacted with them. Additionally, all VR-related documentation and "…information of a technical nature will help in understanding what functionality is required in reconstructing the system either physically or through emulation."[112]

All things considered, more than one approach is likely necessary to preserve a digital

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[110] Kate Fernie and Julian D. Richards. *Creating and Using Virtual Reality: A Guide for the Arts and Humanities*. (Arts and Humanities Data Service, 2002). https://vads.ac.uk/guides/vr_guide/
[111] Ibid.
[112] Baker and Anderson, 22

system as intricate as virtual reality. All of the above approaches will likely need to be used in tandem to achieve the best results. Examples of the original hardware can be stored and preserved, supporting digital documentation and simpler VR-related file types such as 360-degree videos and 3D models can be migrated, and complex software applications can be emulated. "A migration strategy can be used for virtual reality developed using standard formats, for original data files, screen-shots, and associated documentation. Where it is important to preserve the 'look and feel' of the original virtual reality, emulation may be appropriate."[113] Though there are no easy solutions and many works will necessitate consideration on a case-by-case basis, a multi-faceted and holistic approach is one way of looking at the challenges of preserving virtual reality.

Adapting Other Models for VR Preservation

In order to further consider implementing a multi-faceted approach to virtual reality, the holistic preservation models in use by time-based media conservators and video game preservationists could be adapted for use with virtual reality collections. Both of these fields work with complex media objects that depend on interactions between hardware, software, and individual users (game players or museum patrons). I will examine the approaches of these two different fields to evaluate which aspects of them may be useful to consider when designing and implementing a preservation strategy for virtual reality works.

The Video Game Preservation Model

In cultural heritage institutions, video game preservation involves more than preserving

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[113] Fernie, and Richards

just the playable game itself. For example, the Library of Congress strives to save not just a copy of the game, but also information and ephemera surrounding the game to help contextualize it. In practice, this entails saving a copy of the game on a physical carrier (the cartridge or the disc it was released on), as well as the game's box art, manuals, and any advertisements that came with a release copy of the game. All of these items are housed together in acid-free, archival boxes.[114] This strategy falls under the "physical storage" approach to digital preservation. Though it does not ensure the content remains accessible on current computing platforms, it does ensure that the game can be viewed alongside accompanying documentation, which can help contextualize how the game was released.

Under previous copyright laws, video game developers were required to submit videotaped footage of the game and a portion of the game's source code to the Library of Congress. This law was updated in 2006 so that, instead of a video, a copy of the game itself needed to be submitted. However, this update also eliminated the source code deposit requirement as well. The source code the Library of Congress received prior to 2006 was only for the first twenty-five and last twenty-five lines of the games code (an amount so infinitesimal it would tell one extremely little about how the game actually functioned). These lines of code were submitted printed out on paper. With this being the case, the Library of Congress is unable to use these previous deposits of source code for preservation purposes.[115] Without access to a game's source code, migrating the content to a newer format becomes less feasible. David Gibson, a Moving Image Technician at the Library of Congress, advocates for the Library's

[114] "Playing Pong in 2100: How to Preserve Old Video Games – Part 1." Smithsonian American Art Museum. August 8, 2012. Video Recording. https://www.youtube.com/watch?v=g__noQCDZsc

[115] Ibid.

collection policy to include a complete copy of a game's source code.[116]

Beyond these practices, the Library of Congress has also published a Recommended Formats Statement for Software and Electronic Gaming and Learning. Library of Congress recommended formats statements intend to identify "…hierarchies of the physical and technical characteristics of creative formats, both analog and digital, which will best meet the needs of all concerned, maximizing the chances for survival and continued accessibility of creative content well into the future."[117] This statement prioritizes what should be included within an acquisition/deposit to ensure the long-term preservation and accessibility of the object.

For video games, the Library of Congress gives priority to the video game content itself, accompanying documentation (such as manuals and read me files), the operating system, and the computing environment or console. They also prioritize collecting a digital copy of the software's source code as well as metadata about the compiler used to create the final version of the code for the game's release.[118] A compiler is a program that turns the human-readable source code written in a programming language (such as C or Java) into language the computer will read, such as assembly language or machine code. Code needs to be compiled in order to create an executable, playable file. Understanding how code was originally compiled can be valuable in attempting to preserve a piece of software, as sometimes emulation may involve recompiling a

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[116] Trevor Owens. "Yes, The Library of Congress Has Video Games: An Interview with David Gibson." *The Signal.* September 26, 2012. Accessed April 4, 2017. https://blogs.loc.gov/thesignal/2012/09/yes-the-library-of-congress-has-video-games-an-interview-with-david-gibson/

[117] "Library of Congress Recommended Formats Statement." *Library of Congress*. Accessed April 4, 2107. http://www.loc.gov/preservation/resources/rfs/index.html

[118] "Recommended Formats Statement – Software and Electronic Gaming and Learning." *Library of Congress*. Accessed April 4, 2017. http://www.loc.gov/preservation/resources/rfs/softgame.html

game's code in order to get it to run properly.[119]

In addition to the Library of Congress's practices and recommendations, lessons can also be learned from the Preserving Virtual Worlds study on video game preservation. This Library of Congress-funded project examined the preservation of video games, including open world, online, multiplayer games such as *World of Warcraft* and *Second Life*. These large, interactive video game worlds share many similarities with virtual reality software and games, including the issue how of how to preserve an immense and immersive, computer generated environment that multiple users can access and interact with simultaneously. Some of the findings of the first phase of the Preserving Virtual Worlds project can be considered when thinking about preserving virtual reality video games and software.

Based on their research and findings, the authors of the *Preserving Virtual Worlds Final Report* make several recommendations about what archivists should ask for from software developers. This includes a copy of the game's source code, technical documentation relating to the game, original production materials and artwork, and records of interaction from the game's user community:

> The game source code, production assets and the technical documentation acquired and generated in the course of game production are likely to have the greatest direct impact on the preservability of a game. The source code and game assets widen the set of potential preservation strategies, and technical documentation regarding the platform on which the game was intended to run is second only to representation information about the game files themselves in terms of its significance for supporting technical preservation activities. Production materials, oral documentation from game designers, and records of interaction with a game's user community are of great value to anyone seeking to understand the life cycle of a game over time.[120]

This is very similar to the Library of Congress's recommendations for what to acquire when preserving a video game. The main take away from both Preserving Virtual Worlds and the

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[119] McDonough, et al. 22.
[120] McDonough, et al. 23.

Library of Congress's recommendations are that more than just the playable video game content must be saved in order to preserve the work, make it accessible, and contextualize it for researchers. This practice should also be followed when preserving virtual reality systems, and especially when working with virtual reality software and video games. Not only should the VR software be saved, but its source code and supporting documentation as well.

Though emulation and migration are discussed as potential strategies for preservation in the *Preserving Virtual Worlds Final Report*, these methods will be further tested and evaluated in the next phase project, Preserving Virtual Worlds 2 (the final report of which has not yet been published). Building on the findings of the first phase, Preserving Virtual Worlds 2 aims to identify the significant properties of software-based games (what aspects of the works that must be maintained when preservation actions are taken) and will "…investigate how successfully different preservation approaches, including emulation, migration, re-enactment, and documentation strategies, manage to preserve various significant properties of games."[121] This type of research and the evaluation of different digital preservation strategies for video games will be very helpful in terms of indicating how virtual reality works can be preserved as well.

Finally, both virtual reality and traditional video games are highly interactive and have dedicated user communities. Under the old copyright law, the Library of Congress used to collect footage of a video game in lieu of an actual copy of the game itself. As a form of documentation to aid in understanding how virtual reality hardware and software were used, this type of footage should also be collected by cultural heritage institutions. Video footage of what the virtual reality software actually looks like, along with footage of users wearing the virtual reality gear and

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[121] Jerome McDonough. "Preserving Virtual Worlds 2: Researching Best Practices for Video Game Preservation." https://www.cni.org/wp-content/uploads/2011/12/cni_tangled_mcdonough.pdf

showing how they played a game or interacted with a particular type of content will be valuable for understanding both what the content is supposed to look like, as well as how users interacted with it. David C. Brock also recommends this type of "video ethnography" as a way of preserving a form of documentation about the performance of a virtual reality system.[122] Brock and I discussed the possibility of recording the video feed that is going into the virtual reality headset, and saving it as an output format that can be viewed through other, more current models of VR headsets. This way, you could reproduce the video stream of the content without needing the entire VR system to recreate the image.

While being able to view historical VR through more contemporary headsets would provide some sort of documentation of the experience, and attempt to show it through similar display devices, this approach would not preserve any of the interactive elements of VR. With virtual reality, it is meant to be an immersive and interactive experience. According to Brock, "If what you preserve and the means of access never let you have an interactive experience: did you really preserve it? Probably not. You probably just preserved some of the features of it."[123] As with video game preservation, VR software has many dependencies and peripheral equipment, as well as a level of performance and interactivity. This type of user experience needs to be considered when preserving VR. Though recording video footage of user interactions with virtual reality devices and the environments users can see through the lenses of the headset will be valuable to future researchers in understanding how the technology worked and how users interacted with it, these videos should be a form of accompanying documentation and not be considered as the preservation master itself.

[122] Brock
[123] Ibid.

Drawing on these video game preservation strategies can be useful for preserving virtual reality content, including VR video games. Supporting documentation and ephemera can be collected to contextualize the virtual reality work, and in the case of user manuals understand how a particular piece of VR hardware functioned. By saving the source code of a game, migration becomes a feasible preservation strategy and emulation can potentially be more faithfully carried out. Saving video footage of both the virtual environment itself and of users interacting with it can also serve as a valuable piece of documentation in regards to user experience. Taking inspiration from this the multi-faceted, video game preservation can therefore be helpful in thinking about how to implement a similarly multi-faceted approach to virtual reality preservation.

The Time-Based Media Conservation Model

Another potential preservation strategy for virtual reality could also draw from the practices of art conservators who deal with time-based media artworks. In time based-media conservation, preservation and restoration decisions are made with the artist's intent and the overall meaning of the work in mind. Time-based media refers to any artwork where duration is a characteristic of the work. This can include film, video, audio, and computer-based art, as well as virtual reality. The conservation of these artworks entails documenting their creation and installation, planning for their exhibition, and performing preservation, conservation, and restoration work on the art. The methodology behind these processes could also be applied to virtual reality works.

According to Joanna Phillips, time-based media conservator at the Guggenheim Museum, one characteristic of time-based media artworks is that they are, "…unstable by nature: their technological constituents become obsolete, they frequently require adaptation to changing installation environments, and every reinstallation introduces some extent of interpretation."[124] Phillips's description of time-based media art is reminiscent of the issues of preserving historical VR. The hardware and software of that era has been obsolete for at least two decades. The same will someday be true of today's VR as current headset models are either superseded by newer, more advanced models, or the industry fizzles and stagnates again as it did in the mid-1990s. As such, virtual reality, like time-based media art, can be considered unstable by nature. Pip Laurenson, head of time-based media conservation at the Tate, also notes that:

> Time-based media installations exist on the ontological continuum somewhere between performance and sculpture. They are similar to works that are performed, in that they belong to the class of works of art, which are created in a two-stage process…. in the case of a time-based media installation, the work must be experienced as an installed event, which again has parallels with a performance. In terms of the parameters of change, the notion of a performance has a different logic than that of the traditional conservation object, and works that are performed allow for a greater degree of variation in the form they take.[125]

Here, another comparison between virtual reality and time-based media art can be drawn: it has a performative nature. Users must don goggles, and possibly gloves or a vest lined with sensors: the costume for entering the virtual environment. Then they interact with the computer-generated world, an act that David C. Brock also likened to a kind of performance. This interactive, ephemeral (a VR world only exists when one logs in to inhabit it, a time-based media work only

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[124] Caitlin Dover. "What is 'Time-Based Media'?: A Q&A with Guggenheim Conservator Joanna Phillips." Guggenheim.org. March 4, 2014. Accessed March 10, 2016. https://www.guggenheim.org/blogs/checklist/what-is-time-based-media-a-q-and-a-with-guggenheim-conservator-joanna-phillips

[125] Pip Laurenson. "Authenticity, Change and Loss in the Conservation of Time-Based Media Installations." *Tate Papers*, no. 6. Autumn 2006. Accessed March 10, 2016. http://www.tate.org.uk/research/publications/tate-papers/06/authenticity-change-and-loss-conservation-of-time-based-media-installations

exists when it is installed) idea of media art as a performance is another level that virtual reality can be considered on.

In *Inside Installations*, Pip Laurenson proposes a workflow for assessing the preservation risks of a time-based media artwork as follows:

1. Establishing the anatomy of the installation
2. Developing a 'Statement of Significance'
3. Determining the relative value to the whole of the elements identified
4. Developing scenarios and identifying the risks
5. Exploring the possibility of recovering lost value
6. Carrying out a qualitative or (semi)-quantitative assessment of risks[126]

The first step, establishing the anatomy of the installation, constitutes surveying the various components of the work, all of the separate pieces and media that are part of the artwork. For a virtual reality system, its anatomy can include, but is not limited to, the headset; the computer or cell phone used to generate the images; any peripheral devices such as gloves, vests, and controllers; the actual media that is the content being viewed (both visual and audio aspects); and the software such as the device's operating system and the media player application that enables the content to be viewed. Step two, creating a statement of significance, entails identifying which aspects of the work are integral to its meaning and understanding. These are the most important characteristics of the work that must be considered for its preservation. Part of determining what is significant to a work involves bringing the artist, if possible, into the discussion with the conservator and curator about how the work should be handled within the museum's collection. Identifying the significant properties of a particular VR system will be helpful for developing a preservation strategy for it. Does the creator of the content specify that the work needs to be experienced using a particular model of headset? Or can the headset be substituted with a

[126] Pip Laurenson. "The Preservation of Installations". *Inside Installations: Preservation and Presentation of Installation Art*. (Instituut Collectie Nederland, 2007): 40.

different model? How significant of a role do external input devices and accessories play in the meaning and functionality of the virtual reality work? Following Laurenson's model, these are questions a preservationist can ask when dealing with a particular VR work in order to identify risks involved in preserving it for the future and strategies that should be implemented to care for it over time.

In time-based media conservation, involving the artist in the preservation process is one means of maintaining the meaning and authenticity of a work over time. If the work experiences any changes over the course of its life cycle, these changes would thus be approved by the creator of the piece. One method that can be used to encourage this dialog between conservators and artists is the Variable Media Questionnaire, of which Jon Ippolito was a contributor. He developed the Questionnaire to "…stimulate responses that will help us understand those artists' intent… an instrument for determining how artists would like their work to be re-created in the future—if at all."[127] This methodology recognizes that, in conservation, there is no one-size-fits-all solution. The questionnaire is meant to be filled out by the artist and applied by the conservator on a case-by-case basis, one work at a time. Artists' answers to the online questionnaire enter a multi-institutional database that enables cultural heritage institutions to share this data across artworks and collections.

In his discussion of the purpose and uses for the Variable Media Questionnaire, Ippolito briefly mentions some of the other preservation strategies I assessed previously: storage, migration, and emulation. He reviews the effectiveness of these strategies for dealing with complex media art. In terms of physical storage, Ippolito writes: "Storage, the default

[127] Jon Ippolito. "Accommodating the Unpredictable: The Variable Media Questionnaire" *Permanence Through Change: The Variable Media Approach* (Guggenheim Publications and The Daniel Langlois Foundation for Art, Science and Technology, 2003): 47.

preservation strategy for museums from the eighteenth to the twentieth centuries, is proving to be of limited value in the twenty-first."[128] Rather than merely storing the work in a climate-controlled environment, the work should, through discussions with the artist, be updated using a digital preservation method. In the art world, migrating a work, "…is not to imitate its appearance with a different medium, but to upgrade its medium to a contemporary standard, accepting any resulting changes in the look and feel of the work."[129] Emulation, "…by contrast, is not to store digital files on a disk or physical artefacts in a warehouse, but to create a facsimile of them in a totally different medium. An especially promising application of emulation is when new software impersonates old hardware."[130] By implementing emulation or migration as a time-based preservation strategy, the work is allowed to evolve over time, according to how the artist sees fit.

A time-based media conservation approach, when applied to virtual reality, would recognize that VR is an unstable medium that may need to change over time (in a way that is acceptable to the creator's idea of the work) in order to continue being accessible. This approach also recognizes the performative aspect of virtual reality as a medium heavily intertwined with how the user experiences and interacts with both its hardware and the media that plays on it. Perhaps something equivalent to the Variable Media Questionnaire can also be created for artists as well as other content creators working with virtual reality. This way, preservationists can make informed decisions about what actions to take, based on what the artist or developer views as the work's significant aspects.

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[128] Ippolito, 51
[129] Ibid.
[130] Ibid.

Avoiding a Rift in Our Practices: Implementing a Multi-Faceted Preservation Strategy

An important thing to consider when choosing which model to draw from is what kind of virtual reality content being preserved and the collection that it is part of. Is the object of preservation in question a unique, virtual reality art work or a mass-produced VR video game? Museums acquiring virtual reality artworks should try to adapt existing time-based media theories and practices to VR artwork, as it shares similarities with other audiovisual installations. If the institution is a library, museum, or archive that has acquired a collection of more broadly released, non-unique copies of virtual reality video games, then considering implementing strategies from the video game preservation community would likely be more appropriate in that scenario. As such, the context of the collecting institution and its existing practices, as well as the context of the virtual reality collection itself, should both be considered before implementing a VR preservation strategy.

Within their existing frameworks, institutions can then consider which aspects of a VR work are important for them to collect and make accessible to their specific user groups. This can include deciding which pieces of hardware and software to collect, what kinds of documentation about the virtual reality work they require as part of an acquisition, and what preservation strategies they want to implement. In a museum setting where the original hardware is integral to the meaning of a VR artwork, it would be may be deemed important to maintain the original software on its original hardware. In cases where hardware is less significant to the overall meaning, look, and feel of a piece, the cultural heritage institution can then decide on migrating the material to a new format or emulating it on newer VR hardware.

Regardless of the institution or the collection, however, a multi-faceted approach of some nature should be implemented when dealing with virtual reality. Whether the work to be preserved is a one-of-a-kind VR art installation, a 360-degree video file, a 3D model, or a piece of proprietary virtual reality software, these works are all complex and rely on interdependencies between hardware and software to function. User experience should not be forgotten as well, as all varieties of virtual reality are, to one degree or another, interactive experiences. In tandem with these preservation strategies, records of user interaction with virtual reality systems should also be saved, such as through video footage of gameplay, in order to aid cultural heritage institutions and future researchers in understanding how these devices were used. Though many virtual reality works will need to be treated on a case-by-case basis and be considered within the context of the collecting institution acquiring them, the common denominator will be implementing multiple preservation strategies in order to tailor a preservation or conservation plan to a specific virtual reality work or system.

Chapter 6: Next Steps for Virtual Reality Preservation

This thesis has attempted to provide an overview of virtual reality's history and content types, assess how it has thus far been treated within cultural heritage institutions, and present potential strategies for its preservation. In this concluding chapter, I will look towards the future and next steps that need to be taken in order to design and implement virtual reality preservation plans. This will include a discussion of different challenges the cultural heritage community will likely face when dealing with new collections of virtual reality hardware and software. I will also summarize the key concepts about virtual reality's history, collection, and system and content specifications, and preservation recommendations discussed in the previous chapters.

With no commonly accepted preservation workflows or best practices currently in place in archives, museums or libraries, virtual reality preservation is an emerging field with many challenging questions that need to be considered before implementing preservation plans. When I asked Andrew Scherkus, a software engineer working with the Google Spatial Media Group, what he saw as the biggest challenge for creating standards for virtual reality, he responded: "It's still the early days and there are still a lot of unknown unknowns. It's also hard to get a whole industry to agree on something."[131] This concern applies not only to VR content creators and hardware developers, but also to future VR preservationists as well. There are still many unanswered questions about how to preserve virtual reality that will require further research and ongoing discussions within the media archiving community, and agreed-upon standards and practices will need to emerge from these collaborations. These issues include questions about what types virtual reality will be collected and which components will be preserved, as well as

[131] Scherkus

what metadata cultural heritage intuitions will need to consider when describing and preserving VR collection materials.

Which Version to Preserve?

One of the challenges facing preservationists confronted with virtual reality is determining which headset models and versions of software they will be preserving. Virtual reality is still largely conceived of as being in the prototype phase. Even though the Oculus Rift was officially released in 2016, two different prototype models were widely available to software developers prior to this, and content had been produced for the Rift for several years. Following FaceBook's purchase of Oculus in 2014, the Rift was also very prominently being written about and advertised for at least two years prior to its release, and it already seemed as though it was part of the cultural and technological landscape. Though not a VR headset, a similar phenomenon was seen with Google Glass. The augmented reality glasses were widely publicized and advertised, even though they never technically never left the "Beta" phase of development before Google cancelled the project entirely. Again, a large enough quantity of devices was circulating that the Glass was part of the public consciousness, even though, according to Google, it had never officially been released.[132] This type of release model makes the line between prototype and official product very blurry and difficult to distinguish.

Compounding this issue is that VR developers and content creators view the projects they are working on as being in constant development, seeing ways that software can continue to be improved and edited. This extends to not just the hardware, but the virtual reality content itself. At the Virtual Arcade, the virtual reality-devoted program of the Tribeca Film Festival, in 2017,

[132] "Google Glass" Wikipedia. https://en.wikipedia.org/wiki/Google_Glass

several of the virtual reality games and movies shown were brief demos, rather than completed works. Will demos, teasers, and various versions of the VR work created during its production be preserved? If a virtual reality software application is released as different versions on different headset models, how many of them will be preserved? Virtual reality archivists will need to determine how many and which ones. In 2002, more than a decade before the current wave of virtual reality began, the Arts and Humanities Data Services already recognized this problem: "Projects are often seen as transitory experiments and little thought is given to reuse or to their place in the history of VR. One only has to read much of the literature about VR and its origins to realize that projects have physically (in terms of equipment) and digitally (in terms of files) disappeared or been broken up."[133] Another concern here is that, if a VR project languishes in production and is ultimately cancelled, the developers may not consider the prototypes worth saving, and a part of virtual reality's history may consequentially be lost. This already appears to have happened with the VR of the 1980s and 1990s. It is currently unknown how much of the virtual reality software from that era survives today.

To mitigate this issue, the authors of the ADHS guide state, "Perhaps the best way of preserving virtual reality for the future is to consider archiving material from the start of the project and not just at its completion."[134] Following this advice, virtual reality preservationists would need to proactively begin acquiring virtual reality systems for their collections. This proactive approach may also require outreach efforts from the preservation community, and engaging with VR content creators and software companies in a dialog about archiving their material during the production process. From there, issues concerning which versions of virtual

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[133] Fernie and Richards

[134] Ibid.

reality software and hardware should be preserved can be considered from both the production and archival perspectives.

Metadata for the Metaverse

Similar to preserving any other collection materials, from manuscripts and text files to analog and digital audiovisual works, a large part of developing preservation plans for virtual reality includes capturing descriptive, technical, structural, and preservation metadata.

As the examination of the collections of the Computer History Museum and Living Computers: Museum and Labs in chapter 3 demonstrated, accurate descriptive metadata is key to making virtual reality items discoverable and accessible to researchers. Providing thorough descriptive metadata will also aid the preservation process, as it would include detailed information about the virtual reality headset or content, such as when it was made and what company made it. This information could then lead preservationists to determine what kinds of hardware or software dependencies the virtual reality system requires in order to function. As stated in the *Preserving Virtual Worlds Final Report*:

> The primary problem of preserving computer games and interactive fiction is primarily an issue of structural metadata and collection management, insuring that you have the complete set of representation information and context information necessary to render your content information both accessible and apprehensible, and that all of the necessary relationships between content, representation, and context information are appropriately recorded[135]

Ample technical specification and contextual information about the virtual reality system is thus required in order to preserve it and make it accessible to researchers. For descriptive metadata, the authors of *Preserving Virtual Worlds* recommend against using the Dublin Core schema because it is not detailed enough to adequately describe something as complex as an interactive

[135] McDonough, et al. 101-102

video game environment that supports multiple users at once. As such, Dublin Core will likely also not be granular enough to be implemented for virtual reality catalog records. The authors instead recommend considering metadata standards such as MARC/XML, MODS, and VRA Core as they offer more descriptive fields and enable identification of specific editions.[136] As VR hardware and software both have the issue of having many prototype and demo versions, and there may also be different versions of the same software released for the different headset models, a field for identifying the version of the VR item will be very important to include in its record.

Currently, there is no standard metadata schema for virtual reality. This includes all variants of VR content: 3D models, 360-degree video, and interactive software. The preservation community will need to evaluate the different metadata schemas and determine which is the most appropriate for dealing with virtual reality systems. This may include adding fields to existing standards to make them more accommodating to virtual reality.

Standardization Initiatives

Many of the challenges surrounding virtual reality preservation pertain to the fact that there are currently few widely-adopted standards in place for virtual reality, from file formats used to metadata schemas. As Baker and Anderson note:

> The first step in planning the preservation of a digital object (of whatever complexity) is to apply a known standard to the component parts of that object. As an object may have many different components it may be necessary to apply different standards to each different part, and it may be necessary to apply multiple standards to a specific media type depending on the circumstances.[137]

[136] McDonough, et al. 104.
[137] Baker and Anderson, 19.

As virtual reality is a complex system of various hardware and software components (and interactive VR software like video games are themselves packages comprised of a multitude of different digital file types), standards will thus have to be considered for each different part of a VR system. Though much work still needs to be done in the area, there are currently several standardization efforts in progress that will facilitate preservation practices. This includes work by the Google Spatial Media Group and the Khronos Group.

As previously mentioned in Chapter 4, the Google Spatial Media Group is currently working to create standards for 360-degree video. The metadata specifications they are creating are open source and freely accessible on the group's GitHub repository.[138] This includes technical metadata specifications for both 360-degree video and ambisonic audio. These specifications have been incorporated into the Matroska and MP4 wrapper formats. In terms of 360-degree video, the Spatial Media Group's specifications include metadata elements for different projection mappings (such as equirectangular and cube projection), whether the video is 2D or 3D, and what type of software was used to create the video. For ambisonic audio, there are specifications for how many audio channels there are and how they are mapped. This type of technical metadata will be very valuable for preservationists to understand how the content is structured and how it many need to be preserved differently than a standard video or audio file. The Spatial Media Group has also developed a tool called the Spatial Media Metadata Injector, which can be used to embed these technical metadata fields in 360-degree video files. The Spatial Media Metadata Injector can also be used to validate metadata within existing files.[139]

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[138] "Google – Spatial Media" *GitHub* https://github.com/google/spatial-media
[139] Ibid.

Tools such as this will be helpful in preserving 360-degree video files and ensuring their fixity over time.

Another standardization effort currently underway is being carried out by the Khronos Group, a consortium of virtual reality hardware and software companies. One issue for VR developers is that all of the different virtual reality headsets—the Oculus Rift, HTC Vive, PlayStation VR, Samsung Gear VR, etc.—all track user input in different ways. This hardware fragmentation forces content creators to develop different versions of software applications for each of the different headsets, again compounding the preservation issue of what versions of virtual reality content and software to save. To address this issue, the Khronos Group is working to standardize input and tracking across all of the different virtual reality hardware platforms. According to the Khronos Goup's website, "Key components of the new standard will include APIs for tracking of headsets, controllers and other objects This will enable applications to be portable to any VR system that conforms to the Khronos standard, significantly enhancing the end-user experience, and driving more choice of content to spur further growth in the VR market."[140] This initiative will not only benefit VR developers and content creators who want their work to be accessible on as many of the different headsets as possible, but will also benefit virtual reality archivists and preservationists. If fewer instantiations of the same piece of software exist, then it becomes easier to determine which versions should be preserved for the future.

Though standards and best practices will still need to be developed by the cultural heritage community for virtual reality preservation workflows, file formats, and metadata

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[140] "Khronos Announces VR Standards Initiative." *Khronos*. December 6, 2016. Accessed February 9, 2017. https://www.khronos.org/news/press/khronos-announces-vr-standards-initiative

schemas, standardization efforts such as those by the Google Spatial Media Group and the Khronos Group will help facilitate future virtual reality preservation workflows

Summary of Research and Preservation Recommendations

In Chapter 1, I analyzed several different definitions of “virtual reality” to parse out what technologies and content the words can encompass. There, I established virtual reality as a technological system that uses interdependent hardware and software to immerse users in an interactive environment. Though virtual reality is not an exclusively headset-based medium, I decided to focus on the headset-based manifestations of VR as these devices are seeing increasingly wider adoption for consumer entertainment, artistic creations, scientific research, and other uses. As such, virtual reality headsets like the Oculus Rift, HTC Vive, and Samsung Gear VR, as well as the content that plays on them, are becoming part of today’s cultural fabric and will likely find their way into museum and archival collections.

In Chapter 2, I discussed the history and traced the development of virtual reality systems, from early precursors such as the Sensorama Simulator immersive cinema experience and Philco Headsight video surveillance system to today’s wave of virtual reality headsets. Though virtual reality as it is conceived of today first emerged through Ivan Sutherland’s development of the Sword of Damocles headset in 1968, the technology was largely kept out of the public consciousness for the first several decades of its existence, and was primarily used for private scientific research and military applications. In the late 1980s and early 1990s, virtual reality first emerged as a medium for a wide range of applications, from artistic and creative to medical and business use. At that time, VR imagery and narratives were pervasive in popular books, movies, and television shows, and virtual reality video game devices were released for home and arcade use. The hype surrounding VR during that era of its history, however, quickly died down after several disappointing cancellations of VR video game consoles and the release of the widely-criticized Nintendo Virtual Boy. Between the mid-1990s and the mid-2010s, few developments to VR technology were made and the medium largely faded from the public consciousness. This changed with the recent releases of headsets such as the Google Cardboard and Oculus Rift, which have reignited public interest in virtual reality. Understanding virtual reality's history and technological developments will be important for considering what preservation actions to take and how to contextualize VR collection materials for future researchers.

In Chapter 3, I detailed my search for virtual reality collections in cultural heritage institutions. Ultimately, I was able to find two institutions, both technology museums, that had VR in their collections. I compared and contrasted the treatment, including cataloging practices and exhibit displays, of virtual reality within the collections of the Computer History and Living Computers: Museum and Labs. This exploration revealed that neither institution has thus far acquired any software or content for their VR devices, and the headsets are thus exhibited as inert artifacts rather than interactive experiences. This discovery illuminated the need for cultural heritage institutions to consider VR as a systems technology with interdependent hardware and software that need to be preserved together.

In Chapter 4, I outlined the various types of virtual reality content—3D models, 360-degree videos, software, and ambisonic audio—and discussed the preservation challenges associated with each format. I also considered potential preservation file formats for each kind of VR media. Though further research in this area is required and cultural heritage institutions will need to collectively determine acceptable preservation file formats for virtual reality, my initial recommendations are as follows:

- 3D Models: COLLADA (.dae)
- 360-degree video: Matroska (.mkv) container and a lossless video codec such as FFV1
- Ambisonic audio: An uncompressed audio format such as FLAC, WAV, or AIFF
- Software: Save the executable file, as well as the source code in its original script format

In Chapter 5, I evaluated potential preservation strategies for virtual reality, including physical storage of hardware and media, maintaining original hardware systems, migrating older VR files to more sustainable formats, and emulating historical virtual reality software on more current hardware. As VR is ultimately an interactive systems technology with hardware, software, supporting documentation, and user experiences that all need to be preserved, I determined that just one strategy on its own would not be sufficient. Preserving VR will require the implementation of multiple preservation strategies. Examples of original hardware can be stored and preserved, some VR content such as 3D models and 360-degree videos can be migrated to newer and more sustainable file formats, and complex software objects such as video games can be emulated current hardware. In that chapter, I also considered borrowing practices from the fields of video game preservation and time-based media conservation and adapting them for preserving virtual reality systems.

Finally, in this chapter I have discussed several of the lingering challenges cultural heritage institutions will face when preserving virtual reality collections. This includes the current lack of standards for VR metadata schemas and file formats, as well the curatorial issue of determining which virtual reality headsets and content versions should be preserved.

Bridging the Rift: Towards Preserving Virtual Reality

In the process of researching virtual reality and considering how to preserve it, I have identified a series of rifts pertaining the medium. There is the Oculus Rift, of course, which sparked the current wave of virtual reality development, but also a schism within its historical narrative (the gap in development between the VR boom of the early 1990s and today's wave of virtual reality devices), a separation of VR hardware and its software in current cultural heritage collections, and a siloing of information about and development of the different varieties of virtual reality content within disparate fields of research and user groups. Moving forward, virtual reality preservationists should work to bridge these gaps. Virtual reality hardware and software needs to be preserved together as a complete system, and standards need to be implemented in order to best document and preserve virtual reality so its functionality remains sustainable and its history and content can be understood and accessible in the future.

Following the hype surrounding virtual reality in the late 1980s and early 1990s, the medium quickly lost support from developers and interest dwindled in consumer markets. As identified in Chapter 3, there are currently very few institutions collecting historical VR, and those that are collecting it do not have any software or content to display on the headsets. This being the case, it is currently uncertain how much from this period of virtual reality's history survives today. This rift in VR's history serves as a cautionary tale for today's virtual reality: if action is not taken to preserve these systems, they, like the ones before them, may become lost and records of their existence may become scarce.

The biggest takeaway from examining virtual reality collections and different varieties of VR content is that virtual reality systems need to considered holistically. Virtual reality does not exist in the form of a singular object that can be preserved alone. It is a complex system of interdependent hardware devices and software applications that provide interactive and immersive experiences for users. All of these various components need to be considered in tandem when preserving it. As such, implementing a multi-faceted, holistic preservation strategy will be necessary. This may involve the migration of simpler file types (3D models and 360-degree videos), emulation of software, and physical storage and maintenance of hardware such as headsets and input devices. Collecting documentation, such as user manuals, videos of users playing VR games, and other related ephemera, will also be important for preserving the technology and contextualizing it for future researchers.

As more content is created to view through VR headsets and these devices become increasingly ubiquitous on the consumer electronics market and in the public consciousness, virtual reality will likely find its way into archival and museum collections. Preservationists will be confronted with the challenge of preserving virtual reality systems and content. There are currently no best practices in place for preserving virtual reality hardware and software in cultural heritage institutions such as museums, libraries, and archives. At this key moment in virtual reality's history, as it is again poised to either become a culturally pervasive medium or pass as a popular and highly publicized trend, now is the time for the cultural heritage community to begin discussing how to best safeguard VR materials for the future.

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